QIA

QUANTUM INTERNET ALLIANCE

D3.1 Frequency conversion of telecom coherent states to ion-compatible wavelengths

Document History

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1. Abstract

The ability to quantum link different examples of matter would provide powerful new possibilities for quantum networking. Such hybrid quantum systems can combine the different strengths and capabilities of the underlying systems. For example, trapped ions are promising end nodes given their strength in quantum information storage and processing, while solid-state memories are promising repeater nodes given their multi-mode capability, high optical depth and deployability. A promising approach to link these two systems is to use photon frequency conversion, to link their individual photon energies via a common telecom wavelength. Here we report on an experimental step towards this on the ion-trap side: we realise and detail frequency conversion of telecom wavelength light (1550 nm) to our ion compatible wavelength (854 nm). After giving more detail on the context of the work, our setup, results and understanding of the conversion of classical (laser) light are given. Finally, preliminary results on the conversion of real single photons from a trapped ion are briefly summarised.

2. Keyword list

Frequency conversion, telecom, trapped ion, quantum communication, quantum network

3. Acronyms & Abbreviations

DoA	Description of Action
EC	European Commission
WP	Work Package
IQOQI	Institute for Quantum Optics and Quantum Information, Innsbruck, Austria.
ICFO	Fundacio Institut De Ciencies Fotoniques, Barcelona, Spain.
NV	Nitrogen Vacancy

4. Introduction

This report concerns a deliverable that is part of our broader task to integrate our experimental platforms to enable long-distance quantum networking (Task 3.3). In particular, the relevant goal and targeted outcome is to make significant experimental steps towards a quantum connection between specific end nodes and repeater nodes.

The ability to interconnect solid-state quantum memories with end node technologies such as trapped ions or diamond NV centres would enable a powerful hybrid system for quantum networking, combing the quantum information processing abilities of the end node system with the multimode storage and convenience of the solid-state memory. The long-term vision, beyond the scope of QIA, is to efficiently create heralded entanglement over long distances using quantum repeaters based on multimode solid-state quantum memories, and then to transfer this entanglement to the trapped-ion or diamond NV end nodes, by way of single photons. To pave the way towards this long-term integration we pursue two projects that link an end node system (WP1) to a quantum repeater system (WP2), and aim to develop and demonstrate the key techniques that would enable two such systems to be quantum networked using photons.

This report is concerned with experimental progress made towards the connection between a trapped-ion end node (WP1) and a solid state quantum repeater (WP2). Over the three year course of QIA our objective is to demonstrate, on the solid-state memory side, the ability to convert single spin-excitations onto single photons that are bandwidth compatible with trapped ions and frequency convert these photons to the telecom band (ICFO).

On the trapped-ion side, our two-year objective is to demonstrate the ability to herald the absorption of light at the telecom band by a trapped ion, using frequency conversion (IQOQI, UIBK). The first experimental step towards achieving our objective is to frequency convert a telecom coherent state (1550 nm laser beam) to be wavelength compatible with our calcium ion at 854 nm. The rest of this report is concerned with presenting the successful achievement of this deliverable.

As a background, we (IQOQI Innsbruck) have recently performed a detailed study and experimental realisation of single photon conversion from 854 nm to 1550 nm in our lab. Our approach is to employ the difference frequency generation process, where an incoming photon at 854 nm has its frequency reduced via interaction with a pump laser at 1900 nm in a crystal with a strong second-order optical non-linearity. We achieved a high-fidelity polarisation-preserving converter from 854 nm to 1550 nm with a total device efficiency of ~30% for an added photon noise of around 50 counts per second [1]. A key challenge was to understand and minimise added photon noise due to the strong (~1W) pump field. Furthermore, this year we used this system to enable entanglement distribution between an ion and a telecom photon [2].

To study and realise the reverse process (1550 nm photon conversion to 854 nm) required for our research goals in QIA we designed, set up and characterised a new non-linear optical system. While the underlying optical process is the time reverse of the previous work (the difference frequency generation becomes sum frequency generation), we cannot simply run our previous experiment in reverse for many reasons. For example, the in-coupling task into the conversion crystals involves a different combination of wavelengths, the crystal waveguides are multi-mode for certain wavelengths and single mode for others and the end-stage narrowband filtering now must occur at 854 nm instead of 1550 nm. Finally, the underlying source of added photon noise is fundamentally different than before. Consequently, a new setup had to be built and the acheivable efficiency and signal to noise ratio measured.

5. Results

5.1. Conversion of laser light from 1550 to 854nm

Our experimental approach was to begin with single-mode fiber-coupled laser light at 854 nm, frequency locked via a wavemeter to within ~1 MHz of our ion 854 nm transition, convert it to 1550 nm via a first frequency 'down' conversion stage and then couple this into single-mode fiber. This telecom laser light was then converted back to 854 nm in a second frequency 'up' conversion stage. Both stages employed free-space-coupled ridge-waveguide-integrated 55 mm long PPLN crystals custom manufactured by NTT Electronics and a 1901 nm 2 W fiber pump laser. The two stages are now described in more detail. The first stage is a duplicate of the 854 to 1550 nm converter presented in Figure 1 of [1] but without the narrowband 1550 nm filter stages. The new second 'up-conversion' stage involves different custom optics to overlap and in-couple now 854 nm and 1900 nm (pump) laser light at the input and decouple 1550 nm from 1900 nm at the output. Finally, after filtering, the output 854 nm light is coupled into single-mode fiber. The optical system was built and characterised by PhD student Martin Meraner and postdoc Viktor Krutianskii in our ion trapping lab at IQOQI Innsbruck.

5.2. Results and understanding

5.2.1. Efficiency

We injected ~1 mW of 854 nm laser light into the first conversion stage and measured a maximum of 45% efficiency conversion to 1550 nm in the output fiber for 300 mW of 1900 nm pump power (consistent with previous results [1]). The conversion efficiency comparing photon numbers immediately before and after the crystal was 60%, with other losses coming from fiber coupling and other optics. **The second (854 to 1550) stage achieved a total fiber-coupled conversion efficiency of 50% for 300 mW of pump power**. The conversion efficiency comparing photon numbers immediately before and after the crystal was 89%, with other losses coming from fiber coupling and other passive optics. The significantly higher crystal conversion efficiency for 854 nm to 1550 nm (than the reverse) can be understood as follows. The waveguides are multi-mode at 854 nm, and single mode for 1550 nm and 1900 nm. When free-space in-coupling 854 nm light (for the first 'down conversion' stage) it is challenging to avoid exciting higher-order modes of the waveguide which do not convert at the same rates to 1550 nm leading to a lower final efficiency. However, when in-coupling 1550 nm and 1900 nm (for the second 'up-conversion' stage) single-mode coupling is ensured.

5.2.2. Noise

Any process through which the conversion stage can itself generate noise photons at the output wavelength (854 nm) can flood the single-photon signal and this is a critical issue to the viability of any given single-photon conversion process. We have measured that the dominant source of noise at 1550 nm for our long-wavelength pump (1900nm) is anti-Stokes Raman scattering (phonons in the crystal scatter with the pump laser, upshifting their energy to higher values). To study the noise at 854 nm produced by our 1550 nm to 854 nm converter, we injected only 1900 nm power, and counted photons at the output using single photon counting APDs after a 10 nm bandpass filter at 854 nm. For 300 mW of input power (the value that would achieve the maximum conversion efficiency) we measured ~2000 854 nm photons per second (after correcting for finite detector efficiency). The observed quadratic dependence of this noise on the input pump power is consistent with the noise source being the sum frequency generation of the scattered 1550 nm component of the pump laser with the un-scattered component of the pump. This tell us that the measured noise of the photons lies in the ~50 GHz phase matching bandwidth of the conversion process. Therefore, by filtering down to ~ 1 GHz we should expect a factor ~50 reduction in noise, to a few tens of noise counts per second.

We ordered a custom air-spaced etalon filter from SLS Optics for 854 nm with a ~1 GHz linewidth and home built a temperature stabilisation system. After installation we observed the expected reduced noise rate of a few tens of 854 nm noise photon counts per second. The etalon achieves an 80% transmission at our central wavelength, leading to a slightly reduced total 1550 to 854 nm conversion stage efficiency of 40%.

The threshold telecom single photon source rate to achieve a signal-to-noise ratio of > 1 after our converter is therefore a hundred photons per second or more (given the finite conversion efficiency of the device). This is certainly reasonable to expect from a solid-state quantum memory, or a trapped-ion-system photon source.

5.3. Conversion of single photons

We applied our conversion system to photons emitted from our ion end node. That is, trigger by a laser pulse, the ion emitted an 854 nm photon which was then coupled into single-mode fiber, converted to 1550 nm by the down conversion stage and then converted back to 854 nm by up conversion stage. The preliminary and unpublished results show preservation of the single-photon wavepacket shape and an end photon signal-to-noise ratio of ~ 5. This signal-to-noise ratio could be doubled using photon detectors with reduced dark counts and further increased by producing (temporally) shorter photons from the ion, which is the subject of current work.

6. Conclusion

We achieved conversion of telecom laser light to a trapped ion-compatible wavelength of 854 nm with a total fiber-coupled efficiency of 40% for an added photon noise of ~20 counts per second and filtering bandwidth of 1 GHz. This system would therefore be capable of converting telecom photons from an expected solid state quantum memory source while achieving a SNR of greater than one: a key threshold for our future project goals. Finally, in a preliminary experiment we used our system to convert telecom photons originating from our trapped-ion source, achieving a signal-to-noise ratio of ~5. While this value is already above threshold for preserving photon-matter entanglement through the interface, there is significant room and known paths for improvement.

7. References

[1] V. Krutyanskiy, M. Meraner, J. Schupp, B. P. Lanyon, Polarisation-preserving photon frequency conversion from a trapped-ion-compatible wavelength to the telecom C-band, Appl. Phys. B 123, 228 (2017)

[2] V. Krutyanskiy, M. Meraner, J. Schupp, V. Krcmarsky, H. Hainzer, B. P. Lanyon, Light-matter entanglement over 50 km of optical fibre, npj Quantum Information 5, 72 (2019)