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EDITORIAL

Announcing the JMO Series on Quantum Memories

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Journal of Modern Optics recently decided to highlight rapidly developing research topics in the area of laser-matter interactions. To this end, the Journal is introducing a range of Series. A current JMO Series on Attosecond and Strong Field Science already attracted significant attention within the scientific community [1]. This editorial is to announce a Special Series on Quantum Memories. The purpose of this series is to bring together contributions which cover all aspects of quantum memories, ranging from general theoretical concepts to experimental realisations, and practical applications. We especially plan to highlight close connections between theory and experiment, which will ensure the development of quantum memories in different physical scenarios as an enabling technology.

Quantum memories are devices that can store quantum states of light without destroying their quantum information. Already in 2000, DiVincenzo emphasized the importance of being able to interconvert flying qubits, like photons, and stationary qubits, like quantum memories, when he formulated his famous five (plus two) functional requirements that must be met by any quantum computer [2]. During the last decade, Quantum Information Science has evolved into a mature discipline of physics. Inspiring theoretical developments resulted in intense experimental work. Vice versa, experimental and technological developments motivated a wide range of theoretical activities. Large scale quantum information processing devices which offer enormous advantages to scientists and engineers in solving computational and physical problems may not yet be the reality. But enormous progress has already been made.

The research on quantum memories, which we report in this series, constitutes an important milestone towards large scale quantum computing devices. For example, quantum memories are an essential ingredient of any *quantum network*. There they serve as sources and as receivers of quantum information. One of the first task considered for quantum memories was hence the writing of a quantum state of coherent light into an atomic ensemble quantum memory [3]. Already in 1997, Cirac *et al.* [4] proposed to build a quantum internet by connecting distant optical cavities via long optical fibers. In recent years, a lot of progress has been made towards the realisation of such networks in the laboratory (cf. eg. Refs. [5, 6]). Quantum memories not only have to reliably read and release quantum states of light. In order to be useful, they have to do this at a very high speed, for a wide range of optical frequencies, and with very long coherence times [7].

Another task of quantum memories, which is closely related to the above described stopping and retrieving of quantum information, is the realisation of *quantum repeaters* for long distance quantum communication [8]. Many people believe that quantum repeaters will be a key component of any long-distance quantum communication network. When sending single photons over very long distances, transmission losses become unavoidable. To overcome this problem, quantum repeaters combine the long life times of quantum memories with the ability of photons to entangle relatively closely-spaced nodes of communication networks. Distributing the entanglement over very long distances can then be done by performing entanglement swapping operations between neighbouring nodes. This approach is possible only if quantum memories are available.

An observation, which has been made early on by the quantum computing community, is that photons do not interact with each other – even when passing simultaneously through a linear optics network. Entangling gate operations between the quantum states of light are always probabilistic when using only linear optics elements like beam splitters and phase shifters [9]. However, when combining linear optics with single-photon sources, it becomes possible to repeat a quantum gate operation between photons until it succeeds [10]. The trick is to double-encode the relevant quantum information in the states of the photons and in the states of their respective sources, such that it cannot get lost. Under ideal conditions, this approach allows to perform quantum gates with unit success rates. Moreover, high-fidelity linear optics quantum computing requires reliable sources for single photon on demand. Hence quantum memories might soon become an essential component of any *linear optics quantum computing* device.

Other applications of quantum memories include loophole-free Bell tests and *quantum metrology*, especially, when they have the ability to generate highly entangled photon states [11]. Within this issue, Bussières *et al.* publish an article, which reviews the prospective applications of optical quantum memories [12]. Its authors list several experimental approaches and achievements, which have been motivated by these applications. Their aim is to depict the current state-of-the-art of optical quantum memories. Considering the wide range of applications of quantum memories, it is not surprising to find that there is also a wide range of approaches towards their experimental realisation. The considered physical systems are very diverse and range from solid state systems, like quantum dots, NV color centers in diamond, and atomic ensembles is rare-earth doped crystals, to quantum optical systems, like atom-cavity systems and cold atomic gases. Ref. [12] concludes with a focus on prospective quantum memories with built-in non-linear processing capabilities.

In different contexts, the term "quantum memories" can have different meanings. It is not always necessary to insist on the ability to interconvert flying and stationary qubits. More broadly, quantum memories can be defined as devices which are capable of storing useful quantum information over a relatively long time. The first article within this JMO Series, cf. Ref. [13], focusses on this kind of quantum memories. In this article, Wootton asks the question how to best store inherently-fragile quantum states with the help of error-correcting and self-correcting processes. While the review article by Bussières et al. [12] concerns the research area of *physical* quantum memories, the focus of Wootton's tutorial is on *logical* quantum memories. He describes different encodings of quantum information to keep the fidelity high and to elongate decoherence times. In particular, he considers Kitaev's surface codes, which include the famous Toric code [14, 15]. These encodings provide reliable quantum memories but also offer a platform for fault-tolerant quantum computation [16].

In conclusion, current research on quantum memories encompasses a wide range of physical systems and theoretical approaches. The reason for this is that quantum memories are an integral part of almost all quantum technological applications. They need to provide solutions to a wide range of problems. Driven by current technological developments and exciting novel theoretical ideas, the topic of quantum memories brings together researchers with different backgrounds. These include quantum optics, atomic and solid state physics, condensed matter, mathematical physics, and computer science. We hope that you, the reader, will enjoy the papers within the ***JMO Series on Quantum Memories***. To submit your own research, please go to the webpage

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General Instructions for Authors can be found at

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Papers submitted for publication within this Series will be given priority handling during the refereeing process. Moreover, JMO offers two months free online access to all Series papers.

Almut Beige
Board of Editors, *Journal of Modern Optics*
The School of Physics and Astronomy
University of Leeds, Leeds
Email: a.beige@leeds.ac.uk

Jiannis K. Pachos
The School of Physics and Astronomy
University of Leeds, Leeds
Email: j.k.pachos@leeds.ac.uk

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