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Quantum network with individual atoms and photons

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Abstract. Quantum physics allows a new approach to information processing. A grand challenge is the realization of a quantum network for long-distance quantum communication and large-scale quantum simulation. This paper highlights a first implementation of an elementary quantum network with two fibre-linked high-finesse optical resonators, each containing a single quasi-permanently trapped atom as a stationary quantum node. Reversible quantum state transfer between the two atoms and entanglement of the two atoms are achieved by the controlled exchange of a time-symmetric single photon. This approach to quantum networking is efficient and offers a clear perspective for scalability. It allows for arbitrary topologies and features controlled connectivity as well as, in principle, infinite-range interactions. Our system constitutes the largest man-made material quantum system to date and is an ideal test bed for fundamental investigations, e.g. quantum non-locality.

1. INTRODUCTION

Cavity quantum electrodynamics (QED) has long been an area of purely fundamental research. For several decades it has provided a model system for the investigation of fundamental radiation effects at the most elementary level of single atoms and single photons, both in the microwave and the optical domain. In particular the strong coupling that can be achieved between individual quanta of light and matter has led to a unique platform for studying a cornucopia of novel quantum phenomena. In fact, cavity QED is like a brilliant jewel that produces new light when viewed from different angles: For example, in the microwave domain with Rydberg atoms, the radiation field is protected by a superconducting resonator with small dissipation, and all information about the field dynamics is obtained by making measurements on atoms passing through the resonator one at a time [1]. A direct detection of the oscillating microwave field, in turn, is realized in circuit QED where Cooper-pair boxes as artificial atoms are coupled to superconducting strip-line resonators, and where sensitive field detectors can be integrated into the circuit [2]. And, last but not least, the direct observation of individual light quanta is standard in the optical domain where cavity dissipation is the essential channel through which information about the system dynamics is communicated to the outside world [3]. The complementary nature of the optical and the microwave experiments, with different variables under observation, is a constant source of inspiration and a strong driving force in the implementation of new technologies in both domains.

Although at present many fundamental issues, like the quantum-to-classical transition expected for an increasing number of quanta in the system, are hardly explored [4], useful applications of cavity QED are already on the horizon. In that context, a distinctive advantage of the optical domain over the microwave domain is that the relatively high energy of a visible or near-visible photon allows one to perform experiments at room temperature, unless the material system must be cooled to achieve the required performance, while the microwave domain with its low-energy photons requires a low-temperature environment to eliminate the perturbing effect of the thermal background radiation.

The optical domain is therefore especially useful for applications in quantum communication and quantum networking over larger distances where low-temperature links cannot so easily be established. Earth-temperature optical fibres, in contrast, can easily transfer near-visible photons over long distances with hardly any random perturbations. It is in particular the optical domain which provides one with a robust and versatile quantum light source that can be used to exchange energy and information between distant quantum nodes in a cascaded network with arbitrary topology and controlled connectivity, the so-called quantum internet. More generally, optical cavity QED has the potential to conduct experiments with a new and revolutionary tool, not with the relatively crude classical tool like a laser beam with shot-noise dominated amplitude and phase fluctuations, but with a much more subtle quantum tool like a single photon carrying just one quantum of energy and one quantum of information.

2. QUANTUM DEVICES

Several unique properties make optical cavity QED systems ideal for quantum networking [5]. Most of these properties have been investigated individually in a series of ground-breaking experiments during the last decade, but their successful combination in one-and-the-same experiment has been achieved only very recently [6]. Before highlighting this experiment, it seems appropriate to summarize some of the most important cavity QED achievements that have been essential prerequisites in the first realization of an elementary quantum network. Special attention is devoted to the experiments at the Max Planck Institute of Quantum Optics.

2.1 Strong light-matter coupling

Experiments with single quanta of light and matter are all performed in the regime of strong light-matter coupling as otherwise the effect of a single atom on a single photon and, vice versa, a single photon on a single atom is too small to cause an appreciable effect. Strong coupling can be achieved in very small resonators made of mirrors with very high reflectivity. Under these circumstances, the atom behaves like a one-dimensional emitter which interacts predominantly with a single resonant mode of the optical cavity. In this novel radiation regime the transmission of a weak resonant probe laser through the cavity is highly suppressed by a resonant atom [3]. This effect can be employed to detect a single atom and track it in real time with high spatial and temporal resolution [7, 8]. The strong coupling also enhances the emission of light into the cavity, thus suppressing the amount of atomic fluorescence into all the other continuum modes not supported by the cavity.

2.2 High-finesse optical resonator

In order to control the light-matter interaction and to induce photon emissions or absorptions with high efficiency, the atom is addressed with laser beams of well-controlled polarization. This requires an unperturbed optical access with large numerical aperture which experimentally is best achieved in a Fabry-Perot resonator where the atom is sufficiently far away from any light-scattering surface [9]. Towards this goal, the dielectric mirror coating is deposited on top of a super-polished glass substrate which is subsequently coned down for better optical access from a direction orthogonal to the cavity axis. The two mirrors have different reflectivity which reduces the achievable finesse but ensures that light generated inside the cavity is almost exclusively emitted in the direction determined by the mirror with the lower reflectivity. Moreover, the asymmetric design facilitates the coupling of light from the outside into the cavity. Special measures have been taken to prevent mirror birefringence which would split the resonator modes and simultaneously lift the polarization degeneracy which would exclude using polarization quantum bits in cavity QED quantum networks.

2.3 Single-atom localization

An essential prerequisite of optical cavity QED experiments is to reproducibly localize a single atom in the centre of a high-finesse optical cavity, at a position where the atom-photon coupling is strongest and, equally important, well known. This is achieved by a combination of dipole trapping in two (or three) orthogonal blue or red detuned standing light waves [10] and cavity cooling [11, 12] or, most recently, feedback cooling [13, 14]. The standing light waves can spatially be adjusted in such a way that the atom is trapped at the desired position, as verified by means of a CCD camera which records fluorescence light emitted by the atom, for example during cooling intervals and state preparation. Average trapping times of the order of a minute can routinely be achieved. Once an atom is lost, it is replaced by a new one, typically within a few seconds. The experimental duty cycle is thus approaching one. Fine-positioning of the atom in case it jumped to another trap minimum during a heating burst [7, 8] as well as replacing an atom when it is lost is automatically performed with a computer.

2.4 Single-photon generation

Controlled quantum experiments aim to emit single photons on the push of a button. This is achieved by means of a vacuum-stimulated Raman adiabatic passage which drives the atom from one of its ground states to another ground state, without population of an excited state [15, 16]. The scheme suppresses spontaneous emission into radiation modes outside the cavity and thus boosts the photon-generation efficiency in a single mode to a level as high as 60%. Technically, the control laser illuminates the atom and has a slowly increasing intensity. Photon generation into the cavity and simultaneous emission from the cavity occurs around times when the control Rabi frequency equals the atom-cavity coupling constant. The temporal shape of the emitted photon wave packet can be tailored by a proper design of the control laser pulse. Experimentally, wave packet durations between about 250 ns and 5 μs can routinely be achieved. Note that a time-symmetric photon wave packet is required in quantum networking experiments where photons are exchanged between identical network nodes [5].

2.5 Coherent single photons

An essential prerequisite of quantum networking is that the photons which are exchanged between the network nodes are coherent. The coherence properties of the photons generated by the vacuum-stimulated Raman adiabatic passage technique are tested by means of an interference experiment in which two single-photon wave packets are spatially and temporally overlapped on a beam splitter and the photon-detection times in two detectors positioned in the two output ports of the beam splitter are recorded. No coincidence detections are expected in case the two single-photon wave packets are identical and thus coherent. If the two wave packets have different frequencies or, more general, exhibit a different phase evolution, a pronounced quantum beat is observed in the relative detection times of the two photons, provided the time resolution of the two detectors is high enough [17, 18]. If the observed beat has a full visibility, the two photons are coherent with respect to each other, although they are distinguishable due to their different frequencies. Any reduction of the beat visibility, for example due to a random phase evolution or a random arrival time of the photon wave packet, is a signature of reduced coherence.

2.6 Light-matter entanglement

Entanglement and disentanglement are central resources in any quantum information processing experiment. In optical cavity QED, entanglement between a stationary atom and a flying photon is achieved by driving a vacuum-stimulated Raman adiabatic passage into a superposition of two atomic ground states, for example with different orientations of the atomic spin [19]. Due to angular-momentum

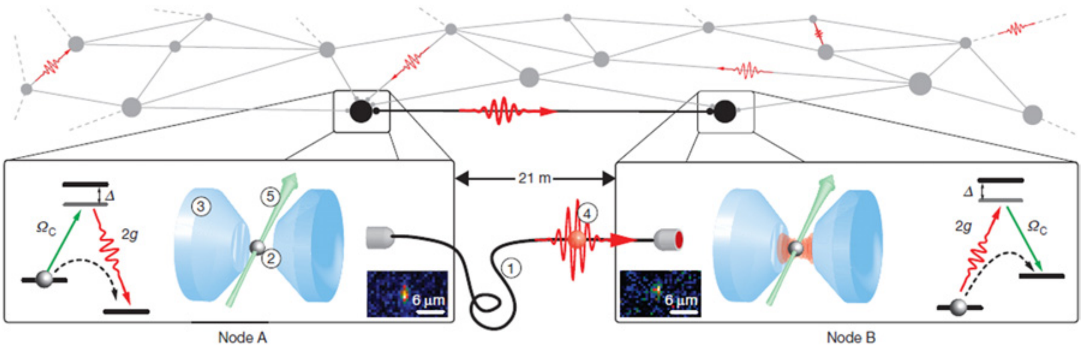

Figure 1. The figure sketches a quantum network with arbitrary topology and controlled connectivity. In the envisaged architecture (top), many single-atom nodes are connected by single-photon links. The properties of a subsystem consisting of two linked nodes (middle; A and B) are presently explored. Details of the nodes and connections are shown in the lower part of the figure. Experimentally, the two nodes are located in independent laboratories connected by a 60 meter long optical fibre ①. Each node consists of a single rubidium atom ② trapped in an optical dipole trap at the centre of a high-finesse optical cavity ③. Quantum state transfer between the atoms and remote entanglement is achieved via the exchange of a single photon ④, with quantum information encoded in the internal state of the atom and the polarization of the photon, respectively. Both the production of a photon (at node A) and its storage (at node B) are achieved via a coherent and reversible stimulated Raman adiabatic passage (with control laser ⑤). Also shown for each node is the atomic level scheme. The green and red arrows indicate the control laser and the exchanged single photon, respectively. The insets show fluorescence images of the two single atoms. The figure is reproduced from Ref. [6].

selection rules, the emitted photon is then in a superposition of two polarization states. As which-path information is not available, even in principle, the atom is entangled with the photon. Disentanglement is achieved by mapping the atomic superposition state onto a second photon, again by driving a vacuum-stimulated Raman adiabatic passage, but this time into a single ground state with a well-defined spin orientation. This state mapping has two consequences: first, instead of the atom the second photon is now entangled with the first photon, and second, the atom is no longer entangled with any of the two photons. The combined fidelity of the complete protocol can be quantified by performing polarization measurements on the two photons emitted one after the other. Large violations of a Bell inequality are observed, thus proving the entanglement of photons that have never overlapped with each other, neither in space nor in time [20].

2.7 Single-atom quantum memory

Besides controlled photon emission from a single atom, quantum networking also requires controlled photon absorption by a single atom [21]. The photon storage process makes use of the fact that the vacuum-stimulated Raman adiabatic passage technique employed for photon generation is in principle reversible. In other words: the photon emission can be reversed to yield photon absorption by adiabatically turning off the control laser upon arrival of the photon at the cavity. Photon storage is monitored by switching the control laser back on at a later time, thus releasing the stored photon. The storage efficiency is remarkably high and amounts to about 15%, probably limited by residual atomic motion and, hence, a not perfectly known atom-photon coupling constant. Beyond the demonstration of single-photon absorption, the atom is also capable of storing the polarization state of an incoming photon in a superposition of two internal spin states. The system thus realizes a single-atom quantum memory for single flying photons; and this with a measured average fidelity exceeding 93% and a coherence time approaching 200 μs [21]. One can expect dramatically longer storage times if the information is stored in atomic clock states.

3. QUANTUM NETWORK

All of the above mentioned achievements were individually implemented and optimized using a single cavity QED system with just one atom. But at least two atoms are required for the demonstration of an elementary quantum network. If these two atoms are separated by a distance not exceeding a wavelength, they can interact with each other in the near field. Energy and information can then easily be transferred between the two atoms. However, the more interesting situation arises when the two atoms are widely separated and near-field effects can be excluded.

One possible solution in this case would be to build a large cavity around both atoms. In fact, cavity-mediated long range light forces between strongly coupled atoms have already been observed more than a decade ago [22]. However, building a large optical cavity around distant atoms poses series technological challenges, one of them being the quest for interferometric stability which is difficult to achieve when it comes to the macroscopic distances required in a fully operational large-scale quantum internet. Moreover, strong coupling is almost impossible to obtain in such long cavities. The single-cavity approach therefore does not open up a promising avenue.

The best solution is therefore to place each atom in its own optical cavity and link the two cavities with an in principle arbitrarily long optical fibre, as shown in the figure. In this case, both cavities can be small, strong coupling can be achieved locally, and interferometric stability between the remote systems is not an issue, at least as long as both cavity QED systems are not part of a larger optical interferometer. Moreover, this approach to quantum networking offers a clear scaling perspective as more and more systems can be added to an already existing network. Another advantage is that the individual cavity QED systems can be arranged in any topology and that two-party links can be established at will, both in time and space.

An elementary quantum network consisting of two optical cavity QED systems, each containing single atoms has recently been realized [6]. The two sub-systems are self-sustaining and are situated in two autonomous laboratories with completely independent infrastructure. The only common equipment is a frequency comb which in both laboratories is used as a reference for the frequency stabilization of the two cavities and the involved lasers. The two atoms are separated by a physical distance of 21 m, and the two cavities are connected by a 60 m long optical fibre which runs over two floors of the building. With this setup, several experiments have already been performed.

3.1 Quantum memory for single flying quantum bits

In a first experiment, a single photon was emitted from one system, the sender node, and send to the other system, the receiver node, for storage. The polarization of the photon was controlled by means of polarization optics so that the capability of the receiver atom to act as a single-photon quantum memory could be tested. Towards this end, the stored polarization state was retrieved by generation of a new photon whose polarization was compared to the polarization of the incoming photon. Average storage fidelities exceeding 92% were deduced from this experiment, well above the classical limit of 2/3.

3.2 Quantum state transfer between two distant atoms

In a second experiment, the atom at the sender node was prepared in a superposition state by first entangling it with a photon whose state was then measured in a well-defined but arbitrary polarization basis. The photon detection process projected the atom into the wanted state which was given by the settings of the polarization optics. After preparation, the atomic state was mapped onto a new photon which was sent to the receiver node and stored there. The polarization information carried by the photon was now encoded in the spin direction of the receiver atom. After an adjustable time delay, the state of the receiver atom was mapped onto another photon which was sent to polarization analyzers to determine the fidelity of the overall protocol, from preparation to detection, with results as high as 84%.

3.3 Entanglement of two distant atoms

In a third experiment, the atom at the sender node was entangled with a photon which was sent to the receiver node. Mapping of the photon state onto the receiver atom produced two entangled atoms, one at the sender node in one laboratory, the other at the receiver node in the other laboratory, 21 m apart from each other. The atomic entanglement was detected by mapping the two atomic states on two photons whose polarizations were analyzed with polarization-sensitive detectors. After post selection, entanglement fidelities exceeding 98% have been observed.

3.4 Nonlocal state rotation

In a fourth experiment, a magnetic field along the quantization direction was applied in order to induce a Zeeman splitting between the two atomic states in which the information about the photon polarization is stored. This periodically rotated the relative phases of these states and thus induced a precession of the atomic superposition state. If the sender atom and the receiver atom were entangled, and if the magnetic field was applied at one location only, this led to a rotation of the entangled state which was observed in correlation measurements on photons emitted from the two nodes.

4. CONCLUSIONS

Already the first experiments which have been performed have demonstrated some of the most essential ingredients of a useful quantum network. Obviously, they followed a long series of experiments performed previously. In fact, experimental progress in atomic cavity QED with the goal to realize an elementary quantum network experienced an almost exponential speed-up during the last two decades. Highlights on this route include the first direct demonstration of strong light-matter coupling for a dilute atomic beam with one atom in an optical cavity on average in 1992 [23] and single laser-cooled atoms dropped through the cavity in 1996 [24]. First landmark experiments with a single atom emitting single photons on demand were performed between 2002 [15] and 2004 [25, 26]. Next steps were taken in 2007 when the photon-generation scheme was extended from one photon to two photons, thus demonstrating two genuine quantum mechanical operations on a single light-matter system [19]. Three successive quantum operations, namely photon generation, photon storage and photon retrieval, were implemented in 2011 by the first realization of a single-atom quantum memory [21]. Remarkably, it took only one more year to make the next step and set up an elementary but in principle fully functional quantum network with four quantum operations, like three photon emissions and one photon absorption, in two distant cavity QED systems in 2012 [6].

In principle, such cascading of quantum operations could also be achieved with free-space emitters, but typical efficiencies would be extremely small and experiments would therefore suffer from intolerably small information-transmission rates [27, 28]. The advantage of cavity QED is that it boosts the overall efficiencies by orders of magnitude [29]. In fact, many of the present limitations experienced by cavity QED experiments come from the finite efficiencies of the classical system components like photon detectors and fibre couplers. Therefore it remains to be seen whether cavity QED progress can continue at such large pace. But the recent demonstration of the teleportation of an atomic quantum state from one cavity QED system to another remote cavity QED system [30] shows that many more exciting developments will evolve in the years to come.

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References

[1] J. M. Raimond, M. Brune, S. Haroche, Rev. Mod. Phys. **73**, 565 (2001).
[2] D. Bozyigit, C. Lang, L. Steffen, J. M. Fink, C. Eichler, M. Baur, R. Bianchetti, P. J. Leek, S. Filipp, M. P. da Silva, A. Blais, A. Wallraff, Nat. Phys. **7**, 154 (2011).
[3] G. Rempe, R. J. Thompson, R. J. Brecha, W. D. Lee, H. J. Kimble, Phys. Rev. Lett. **67**, 1727 (1991).
[4] J. M. Fink, L. Steffen, P. Studer, L. S. Bishop, M. Baur, R. Bianchetti, D. Bozyigit, C. Lang, S. Filipp, P. J. Leek, A. Wallraff, Phys. Rev. Lett. **105**, 163601 (2010).
[5] J. I. Cirac, P. Zoller, H. J. Kimble, H. Mabuchi, Phys. Rev. Lett. **78**, 3221 (1997).
[6] S. Ritter, C. Nölleke, C. Hahn, A. Reiserer, A. Neuzner, M. Uphoff, M. Mücke, E. Figueroa, J. Bochmann, G. Rempe, Nature **484**, 195 (2012).
[7] P. W. H. Pinkse, T. Fischer, P. Maunz, G. Rempe, Nature **404**, 365 (2000).
[8] C. J. Hood, T. W. Lynn, A. C. Doherty, A. S. Parkins, H. J. Kimble, Science **287**, 1447 (2000).
[9] G. Rempe, R. J. Thompson, H. J. Kimble, R. Lalezari, Opt. Lett. **17**, 363 (1992).
[10] S. Nußmann, M. Hijlkema, B. Weber, F. Rohde, G. Rempe, A. Kuhn, Phys. Rev. Lett. **95**, 173602 (2005).
[11] P. Maunz, T. Puppe, I. Schuster, N. Syassen, P.W.H. Pinkse, G. Rempe, Nature **428**, 50 (2004).
[12] S. Nußmann, K. Murr, M. Hijlkema, B. Weber, A. Kuhn, G. Rempe, Nat. Phys. **1**, 122 (2005).
[13] A. Kubanek, M. Koch, C. Sames, A. Ourjoumtsev, P. W. H. Pinkse, K. Murr, G. Rempe, Nature **462**, 898 (2009).
[14] M. Koch, C. Sames, A. Kubanek, M. Apel, M. Balbach, A. Ourjoumtsev, P. W. H. Pinkse, G. Rempe, Phys. Rev. Lett. **105**, 173003 (2010).
[15] A. Kuhn, M. Hennrich, T. Bondo, G. Rempe, Appl. Phys. B **69**, 373 (1999).
[16] A. Kuhn, M. Hennrich, G. Rempe, Phys. Rev. Lett. **89**, 067901 (2002).
[17] T. Legero, T. Wilk, M. Hennrich, G. Rempe, A. Kuhn, Phys. Rev. Lett. **93**, 070503 (2004).
[18] H. P. Specht, J. Bochmann, M. Mücke, B. Weber, E. Figueroa, D. L. Moehring, G. Rempe, Nat. Phot. **3**, 469 (2009).
[19] T. Wilk, S. C. Webster, A. Kuhn, G. Rempe, Science **317**, 488 (2007).
[20] B. Weber, H.P. Specht, T. Müller, J. Bochmann, M. Mücke, D.L. Moehring, G. Rempe, Phys. Rev. Lett. **102**, 030501 (2009).
[21] H. P. Specht, C. Nölleke, A. Reiserer, M. Uphoff, E. Figueroa, S. Ritter, G. Rempe, Nature **473**, 190 (2011).
[22] P. Münstermann, T. Fischer, P. Maunz, P. W. H. Pinkse, G. Rempe, Phys. Rev. Lett. **84**, 4068 (2000).
[23] R. J. Thompson, G. Rempe, H. J. Kimble, Phys. Rev. Lett. **68**, 1132 (1992).
[24] H. Mabuchi, Q. A. Turchette, M. S. Chapman, H. J. Kimble Opt. Lett. **21**, 1393 (1996).
[25] J. McKeever, A. Boca, A. D. Boozer, R. Miller, J. R. Buck, A. Kuzmich, H. J. Kimble, Science **303**, 1992 (2004).
[26] M. Keller, B. Lange, K. Hayasaka, W. Lange, H. Walther, Nature **431**, 1075 (2004).
[27] D. L. Moehring, P. Maunz, S. Olmschenk, K. C. Younge, D. N. Matsukevich, L.-M. Duan, C. Monroe, Nature **449**, 68 (2007).
[28] J. Hofmann, M. Krug, N. Ortegel, L. Gérard, M. Weber, W. Rosenfeld, H. Weinfurter, Science **337**, 72 (2012).
[29] M. Hijlkema, B. Weber, H. P. Specht, S. C. Webster, A. Kuhn, G. Rempe, Nat. Phys. **3**, 253 (2007).
[30] C. Nölleke, A. Neuzner, A. Reiserer, C. Hahn, G. Rempe, S. Ritter, archiv:1212.3127v1.