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Towards Long-Distance Quantum Communication

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Abstract: We study Erbium-doped $LiNbO_3$ waveguides for storage and readout of light pulses based on stimulated photon-echoes. Our results are promising in view of storage of single-photon quantum states as required for a quantum repeater.

OCIS codes: (999.9999) quantum communication; (210.4680) optical memories

Introduction

The last years have seen a remarkable advance of experimental quantum communication, in particular of quantum cryptography that promises information-theoretic secure communication [1]. Yet, many problems still have to be overcome before a quantum secured communication network will be available. A major challenge concerns the increase of the transmission distance, which can be met by means of a quantum repeater [2], requiring the distribution, purification and swapping of entanglement, and quantum memories. While many schemes for storage of non-classical light have been proposed, experimental demonstrations are still at an early stage [3], and efficient, reversible transfer of quantum information between different species has not yet been accomplished.

In this paper we report on the storage, recall and measurement of classical optical pulses via stimulated photon echoes [4], which provides an important test-bed for future quantum state storage based on controlled reversible inhomogeneous broadening (CRIB) of a single atomic absorption line [5]. The experiment took advantage of an Er^{3+} doped $LiNbO_3$ crystal with waveguiding structure, cooled to a temperature of 3.4 Kelvin. These waveguides are interesting candidates for the realization of CRIB, as interaction lengths of many centimetres can be achieved, allowing for large absorption even at low doping concentration. In addition, the 1.53 μm, $^4I_{15/2}\rightarrow{}^4I_{13/2}$ transition in Erbium can feature coherence times in the ms range [6], and is well matched to standard telecommunication fibre, which allows future interfacing of such a memory with the standard telecommunication fibre network.

Photon-echo based storage of classical light pulses

A common approach to storage and retrieval of light is based on three-pulse photon echo (3PE), also known as stimulated photon echo [5]. In this process a first, strong, optical *write* pulse excites the medium, creating an atomic coherence. The *data* pulses, a sequence of pulses encoding the information to be stored, are sent into the medium some time after the write pulse, and transfer the coherence into a frequency-dependent population grating in the ground and excited states. To retrieve the information, a third, strong, *read* pulse is used, which scatters off the grating and causes a photon echo to be emitted a time after the read pulse that is equal to the time separation between write and data pulse. If certain conditions for excitation energy and absorption depths are met, the echo is, to a high degree, an amplitude and phase replica of the stored data pulses.

Now, consider two data pulses (D1, D2) with equal amplitude and relative phase φ (Fig. 1). The 3PEs appear at times $t_e = t_r + t_{Di} - t_w$ (i = 1, 2), where t_r is the arrival time of the readout, t_{Di} the arrival time of data pulse Di (i = 1, 2), and t_w the arrival time of the write pulse. The echoes will thus be $dt = t_{D2} - t_{D1}$ apart. Because the efficiency of the 3PE is at best a few percent [7], much of the frequency-dependent population grating is preserved in the atomic ensemble after the read pulse. Therefore more echoes can be produced by sending in several read pulses. In our experiment, two subsequent read pulses were used to produce two copies of the data pulse. If we chose the distance between the read pulses to be dt, the same as the distance between the two data pulses D1 and D2, the echo of the second data pulse read out by the first read pulse (D2|R1), and the echo of the first data pulse read out by the second read pulse (D1|R2), will overlap and interfere (Fig. 1 c). The intensity of the echo in the central time interval (time-bin) is thus controlled by the phases of the write, the data and the read pulses, i.e. α1, α2/3, and α4/5, respectively.

The sequence of two data pulses is related to what is known in quantum communication as a time-bin qubit [8]: a coherent superposition of a photon being in two non-overlapping time-bins. In our experiment, classical (strong) coherent pulses were used, with width smaller than the temporal spacing dt between the two pulses; the state of light is thus described by a Poisson distribution of photons ($n\sim10^8$), each of them being in a qubit state. Note the similarity of our experiment with a setup containing two interferometers, as used for phase-coding quantum

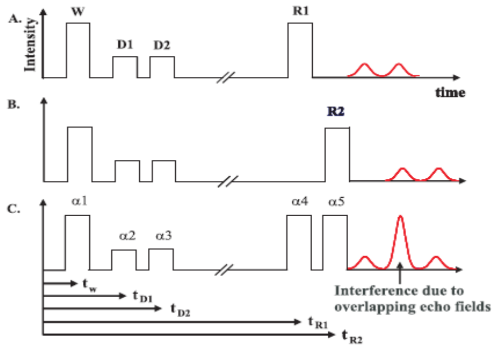

Fig. 1: Illustration of the pulse sequence for photon-echo interference.

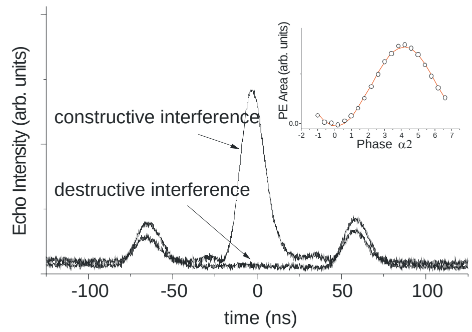

Fig. 2: Photon echo signals showing constructive and destructive interference. Inset: Central echo area as a function of phase.

cryptography [1]: one interferometer prepares the time-bin qubits, i.e. our two data pulses, while the second allows the projection measurement, i.e. our two read pulses.

To create the required pulse sequences, we used an external-cavity cw diode laser (λ=1531 nm), fibre optic phase and intensity modulators, an erbium doped fiber amplifier, and an acousto-optical modulator. The resulting pulses had durations of t_{pulse}=15 ns, with peak powers of around 5 mW for the write pulses, and 1 mW for the other pulses. The first data pulse was created at t_{D1} = 0.6μs, the time between the data pulses was typically dt = 60ns, and the read-out pulses were further delayed by 1 to 2 μs. The light was then coupled into the Er-doped $LiNbO_3$ crystal with waveguide [9], which was cooled to 3.4 K by means of a pulse tube cooler. A magnetic field of about 0.2 Tesla was applied parallel to the C_3 axis, resulting in a coherence time T_2 of about 6 μs [10]. Finally, the photon echoes were detected by a fast photo detector and displayed on an oscilloscope. The clock frequency was of 30 Hz, which ensured that most atomic excitations had decayed between two subsequent storage/recall sequences.

Figure 2 shows observed photon echoes in the case of constructive and destructive interference in the central time-bin, obtained via variation of the phase between the data pulses. The inset depicts the background subtracted area under the peak in the central bin as a function of the phase difference. Note that the background was of purely electronic origin and that no coherent or incoherent back- ground light was interfering with the echoes. We obtained similar results when varying the phase between the readout pulses.

Conclusions

Our findings show that Erbium-doped crystalline waveguides are promising material candidates for all-optical storage. Furthermore, the high visibility in the interference experiments clearly demonstrates that the relative phase of data pulses can be preserved during storage in the optical memory, and that storage can be combined with projection measurements, as required in quantum communication and computation schemes. While our experiments have been performed with classical pulses and (low efficient) traditional photon echoes, we believe that our scheme can be extended to highly efficient quantum state storage based on CRIB.

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References

1 N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, Rev. Mod. Phys. **74**, 145 (2002).
2 H.J. Briegel, W. Dürr, J.I. Cirac, and P. Zoller, Phys. Rev. Lett. **81**, 5932 (1998) .
3 B. Juulsgard *et al*., Nature **432**, 482 (2004), T. Chanelière *et al*., Nature **438**, 833 (2005), M.D. Eisaman *et al*., Nature **438**, 837 (2005).
4 T.W. Mossberg, Opt. Lett. 7, **77** (1982), M. Mitsunaga, Opt.and Quant. Electr. **25**, 1137 (1992), M. Staudt *et al*., Phys. Rev. Lett. **98**, 113601 (2007).
5 M. Nilsson and S. Kröll, Optics Communications **247**, 393 (2005), B. Kraus *et al*, Phys. Rev. A **73**, 020302(R), A. Alexander *et al*, Phys. Rev. Lett. **96**, 043602 (2006), N. Sanguard *et al*., quant-ph/0611165.
6 T. Böttger, C.W. Thiel, Y. Sun, and R.L. Cone, Phys. Rev. B **73**, 075101 (2006).
7 T. Wang, C. Greiner, J. R. Bochinski, and T. W. Mossberg, Phys. Rev. A **60**, 757 (R) (1999).
8 J. Brendel, N. Gisin, W. Tittel, and H. Zbinden, Phys. Rev. Lett. **82**, 2594 (1999), W. Tittel and G. Weihs, Quant. Inf. Comp. **1**, 3 (2001).
9 I. Baumann *et al*., Appl. Phys. A **164**, 33 (1997).
10 Y. Sun et al, J. Lumin. **98**, 281 (2002).