



光学腔增强Duan-Lukin-Cirac-Zoller量子记忆读出效率的研究

马腾飞 王敏杰 王圣智 焦浩乐 谢燕 李淑静 徐忠孝 王海

Experimental study of retrieval efficiency of Duan-Lukin-Cirac-Zoller quantum memory by optical cavity-enhanced

Ma Teng-Fei Wang Min-Jie Wang Sheng-Zhi Jiao Hao-Le Xie Yan Li Shu-Jing Xu Zhong-Xiao Wang Hai

引用信息 Citation: *Acta Physica Sinica*, 71, 020301 (2022) DOI: 10.7498/aps.71.20210881

在线阅读 View online: <https://doi.org/10.7498/aps.71.20210881>

当期内容 View table of contents: <http://wulixb.iphy.ac.cn>

您可能感兴趣的其他文章

Articles you may be interested in

原子系综中光学腔增强的Duan-Lukin-Cirac-Zoller写过程激发实验

Optical cavity enhancement experiment of Duan-Lukin-Cirac-Zoller writing excitation process in atomic ensemble

物理学报. 2021, 70(7): 070302 <https://doi.org/10.7498/aps.70.20201394>

读出效率对光与原子纠缠产生的影响

Dependence of performance character of photon-atom entanglement source on retrieval efficiency

物理学报. 2019, 68(2): 020301 <https://doi.org/10.7498/aps.68.20181314>

量子存储研究进展

Research progress of quantum memory

物理学报. 2019, 68(3): 030307 <https://doi.org/10.7498/aps.68.20190039>

多模式固态量子存储

Multimode solid-state quantum memory

物理学报. 2019, 68(3): 030303 <https://doi.org/10.7498/aps.68.20182207>

基于 $\text{EuCl}_3 \cdot 6\text{H}_2\text{O}$ 晶体的光存储

Atomic frequency comb optical memory in $\text{EuCl}_3 \cdot 6\text{H}_2\text{O}$ crystal

物理学报. 2021, 70(16): 160302 <https://doi.org/10.7498/aps.70.20210648>

冷原子系综内单集体激发态的相干操纵

Coherent manipulation of single collective excitations in a cold atomic ensemble

物理学报. 2018, 67(22): 224203 <https://doi.org/10.7498/aps.67.20181183>

光学腔增强 Duan-Lukin-Cirac-Zoller 量子记忆读出效率的研究*

马腾飞¹⁾²⁾ 王敏杰¹⁾²⁾ 王圣智¹⁾²⁾ 焦浩乐¹⁾²⁾ 谢燕¹⁾²⁾
李淑静^{1)2)†} 徐忠孝¹⁾²⁾ 王海¹⁾²⁾

1) (山西大学光电研究所, 量子光学与光量子器件国家重点实验室, 太原 030006)

2) (山西大学, 极端光学协同创新中心, 太原 030006)

(2021 年 5 月 10 日收到; 2021 年 9 月 24 日收到修改稿)

量子中继是长距离纠缠分发的关键组成部分, 而基于原子系综存储的读出效率是量子中继能否实用化的一个重要指标. 本文利用冷原子系综中的自发拉曼散射过程产生 Duan-Lukin-Cirac-Zoller 量子记忆, 在原子系综周围搭建环形腔, 增强光与原子相互作用, 从而提高读出效率, 然而, 腔内原子的能级分裂使量子记忆的读出效率降低. 本文研究了读出效率随读光相对于原子共振线失谐量的变化关系. 结果显示: 当读光的失谐量为 80 MHz 时, 本质读出效率为 45%, 这时腔对读出效率的增强倍数为 1.68 倍.

关键词: 量子记忆, 读出效率, 光学环形腔

PACS: 03.67.-a, 03.67.Bg, 03.65.Ud

DOI: 10.7498/aps.71.20210881

1 引言

量子通信^[1-3]依赖于量子纠缠的远距离分发, 但量子态传输过程中的通道损耗及退相干^[4-8], 限制了其传输距离 (小于 500 km)^[5,9]. 由于量子不可克隆原理, 其不能像经典信号一样直接放大, 因此量子中继的方案应运而生. 有多种量子系统可以作为量子节点, 例如单原子^[10,11]、单离子^[12]、原子系综^[1]、金刚石 NV 色心^[13]和稀土离子掺杂固态晶体^[14,15]等. 其中基于冷原子系综和线性光学的 Duan-Lukin-Cirac-Zoller(DLCZ) 协议, 由于其能够产生并存储纠缠, 被视为最有潜力的方案之一^[16]. 在该方案中, 先将一束相对于原子共振线失谐的写光脉冲作用到原子上, 经由自发拉曼散射^[17], 以较低几率在空间中发射一个斯托克斯光子, 并在原子

中存储一个与其关联的自旋波. 经过一段时间存储以后, 一束强的读光作用于原子, 将自旋波转换为反斯托克斯光子读出. 在此过程中读出效率是量子中继能否实用化的一个重要指标. 而且读出效率会影响两个相邻中继器节点之间的每一次纠缠交换, 据理论估计, 当纠缠分发距离平均小于 600 km 时, 读出效率提高 1% 可以提高至少 10% 的量子纠缠分发速率^[1]. 通常通过优化读光脉冲^[18], 增大原子系综光学厚度 (OD)^[19,20]和腔增强^[18,21]等方法来提高读出效率. 所谓腔增强, 就是在原子气室外放置一个中等精细度的环形腔, 在空间上约束光场, 来增加光与原子相互作用强度, 有效地提高量子存储器的读出效率. 本文进行了原子系综中光学腔增强的读出效率的实验研究, 研究了读光相对于共振线的失谐量对读出效率的影响, 结果表明: 失谐量为 80 MHz 时, 加腔情况下读出效率是无腔时的

* 国家重点基础研究发展计划 (批准号: 2016YFA0301402)、国家自然科学基金 (批准号 11475109, 11974228, 11604191) 和山西省“1331 工程”重点学科建设计划 (批准号: 1331KSC) 资助的课题.

† 通信作者. E-mail: lishujing@sxu.edu.cn

1.68 倍. 本质恢复效率达到 45%.

2 实验装置与能级结构

实验中将磁光阱 (MOT) 俘获的 ^{87}Rb 冷原子作为存储介质. 整个实验的重复频率为 20 Hz, 如图 1 所示, 在前 42 ms 内开启 MOT 进行原子系综的俘获, 接下来的 8 ms 内, 先进行 8 μs 的态制备, 将原子制备到后续实验所需能级上, 然后进行循环多次实验, 循环过程通过 FPGA (field programmable gate array) 模块来控制, 每个循环包含三个过程, 态清洗、写过程、和读过程. 实验流程为: 两束频率分别为 $|5S_{1/2}, F=2\rangle \rightarrow |5P_{1/2}, F'=2\rangle$ 和 $|5S_{1/2}, F=2\rangle \rightarrow |5P_{1/2}, F'=1\rangle$, 脉宽为 200 ns 的圆偏振光作用到原子上, 将原子均匀地制备在 $|5S_{1/2}, F=1\rangle$ 的 Zeeman 子能级. 随后一束脉宽为 250 ns 的左旋圆偏振的写光与原子相互作用, 其频率锁定在 $|5S_{1/2}, F=1\rangle \rightarrow |5P_{1/2}, F'=2\rangle$ 跃迁负失谐 Δ 处, 经自发拉曼散射过程发射出与 $|5P_{1/2}, F=2\rangle \rightarrow |5F_{1/2}, F'=2\rangle$ 相对应的 $|R\rangle$ ($|L\rangle$) 写出光子, 与此同时在原子系综存储一个与写出光子对应的 $|\sigma^+\rangle$ ($|\sigma^-\rangle$) 自旋波. 存储一段时间后, 一束脉宽为 250 ns 的锁定频率为 $|5S_{1/2}, F=2\rangle \rightarrow |5P_{1/2}, F'=1\rangle$ 跃迁负失谐 Δ 处的右旋圆偏振的读光通过电磁感应透明过程将原子系综的自旋波读

出, 转换为与 $|5P_{1/2}, F=1\rangle \rightarrow |5F_{1/2}, F'=1\rangle$ 对应的 $|L\rangle$ ($|R\rangle$) 的读出光子.

实验装置示意图如图 2 所示. 环形腔由 45° 全反 HR1, HR2, HR3 和 HR4, 反射率为 80% 的 0° 耦合镜 BS1 和反射率为 99.7% 的 0° 耦合镜 BS2 构成. 实验中环形腔的腔长约为 3.3 m, 腔的精细度为 13.5. 腔内总损耗为 21%, 其中腔镜损耗为 15%, 真空原子气室的损耗为 6%. 将原子系综放置在 HR1 和 HR4 之间, 并且在原子系综的两端对称处放置了两个 $F=800$ mm 的透镜, 来满足环形腔内存储实验对信号光束腰的要求, 并且将光斑束腰调至原子处. 由于环形腔内反射镜和透镜对不同偏振光折射率的不同导致的相位差, 采用一对 1/2 玻片和 1/4 玻片的玻片组对这个相位差进行补偿, 其中一个 1/4 玻片放置在原子一端, 另一个 1/4 玻片放置在原子另一端.

实验中读光和写光从雪茄型原子长轴方向的相反方向作用于原子系综, 原子附近腔的光路与读写光路成 5.1° 夹角. 对于读出光子和写出光子, 经由拉曼过程后, 沿近原子长轴方向散射进入腔内. 读出光子沿顺时针在腔内循环, 经由耦合镜 BS1 出腔进入读接收光路, 并且用单光子探测器 SPD1 收集. 写出光子沿逆时针在腔内循环, 以不同角度从耦合镜 BS1 出腔, 进入写接收光路, 由单光子探测器 SPD2 进行收集.

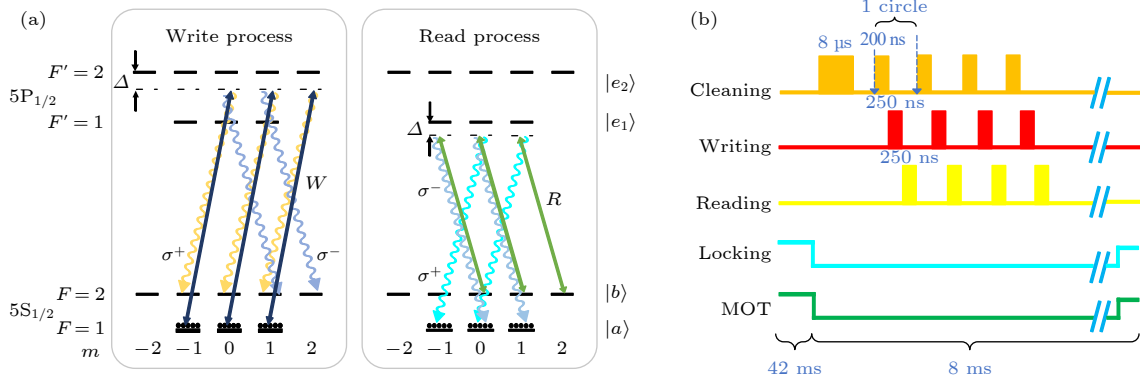


图 1 (a) ^{87}Rb 原子能级. 其中左图为写过程, σ^+ (σ^-) 分别代表左 (右) 旋圆偏振的斯托克斯光, W 代表写光光场. 右图为读过程, σ^+ (σ^-) 代表左 (右) 旋圆偏振的反斯托克斯光, R 代表读光光场; Δ 代表读光和写光相对于原子共振跃迁线的失谐; (b) 实验时序图, 图中 Cleaning 为态制备过程, Writing 代表写过程, Reading 代表读过程, Locking 表示腔锁定时序, MOT 代表冷原子俘获过程

Fig. 1. (a) Relevant ^{87}Rb atomic levels. The left is writing process, σ^+ (σ^-) represents left (right) polarization of Stokes, W represents writing field. The right is reading process, σ^+ (σ^-) represents left (right) polarization of anti-Stokes, R represents reading field; Δ denotes the detuning of the reading and writing laser relative to the resonance transition; (b) time sequence of experimental cycle, Cleaning: the state cleaning process, Write: the writing process, Reading: the reading process, Locking: the locking cavity process, MOT: the cold atom preparation process.

加速度逐渐变大. 本文研究了读光相对于原子共振线的失谐对恢复效率增强的影响. 如图 3 表明: 在有环形腔的情况下, 随着读光失谐变大读出效率逐渐变大. 当失谐大于 80 MHz 时, 读出效率趋于平缓. 在 80 MHz 时读出效率相比于无腔时增强了 1.68 倍, 对应的本质效率为 45%.

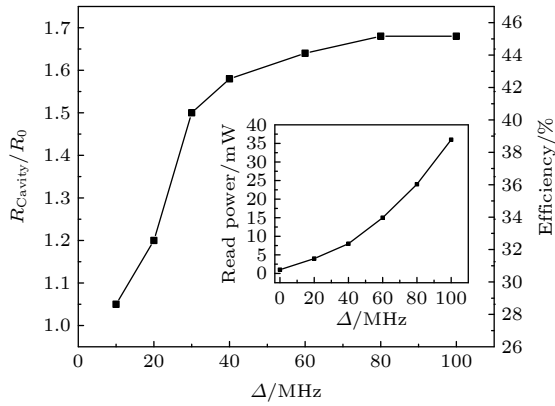


图 3 读出效率的增强倍数和读出效率随着读光失谐量的变化

Fig. 3. The variation of enhancement factor of retrieval efficiency and retrieval efficiency with the detuning of reading laser.

4 结 论

本文在自由空间 DLCZ 量子存储方案的基础上, 开展了光学腔增强 DLCZ 量子记忆读出效率的实验研究. 通过读光失谐来调节腔膜与原子线之间的失谐, 减小腔膜与原子线共振造成的共振峰劈裂, 进而减小劈裂对读出效率腔增强的影响. 经研究得知: 当失谐大于 80 MHz 时, 读出效率趋于平缓, 当读光的失谐量为 80 MHz 时, 读出效率相比

于无腔时增强了 1.68 倍, 对应的本质效率为 45%.

参考文献

- [1] Sangouard N, Simon C, de Riedmatten H, Gisin N 2011 *Rev. Mod. Phys.* **83** 33
- [2] Simon C 2017 *Nat. Photonics* **11** 678
- [3] Bussi eres F, Sangouard N, Afzelius M, de Riedmatten H, Simon C, Tittel W 2013 *J. Mod. Opt.* **60** 1519
- [4] Inagaki T, Matsuda N, Tadanaga O, Asobe M, Takesue H 2013 *Opt. Express* **21** 23241
- [5] Korzh B, Lim C C W, Houlmann R, Gisin N, Li M J, Nolan D, Sanguinetti B, Thew R, Zbinden H 2015 *Nat. Photonics* **9** 163
- [6] Chen G H, Wang H C, Chen Z F 2015 *Front. Phys.* **10** 1
- [7] Chrapkiewicz R, Wasilewski W 2012 *Opt. Express* **20** 29540
- [8] Briegel H J, Dur W, Cirac J I, Zoller P 1998 *Phys. Rev. Lett.* **81** 5932
- [9] Gisin N 2015 *Front. Phys.* **10** 100307
- [10] Reiserer A, Rempe G 2015 *Rev. Mod. Phys.* **87** 1379
- [11] Volz J, Weber M, Schlenk D, Rosenfeld W, Vrana J, Saucke K, Kurtsiefer C, Weinfurter H 2006 *Phys. Rev. Lett.* **96** 030404
- [12] Duan L M, Monroe C 2010 *Rev. Mod. Phys.* **82** 1209
- [13] Gao W B, Imamoglu A, Bernien H, Hanson R 2015 *Nat. Photonics* **9** 363
- [14] Clausen C, Usmani I, Bussi eres F, Sangouard N, Afzelius M, de Riedmatten H, Gisin N 2011 *Nature* **469** 508
- [15] Saglamyurek E, Sinclair N, Jin J, Slater J A, Oblak D, Bussi eres F, George M, Ricken R, Sohler W, Tittel W 2011 *Nature* **469** 512
- [16] Lo Piparo N, Razavi M 2013 *Phys. Rev. A* **88** 012332
- [17] Duan L M, Lukin M D, Cirac J I, Zoller P 2001 *Nature* **414** 413
- [18] Novikova I, Phillips N B, Gorshkov A V 2008 *Phys. Rev. A* **78** 021802(R)
- [19] Bao X H, Reingruber A, Dietrich P, Rui J, D uck A, Strassel T, Li L, Liu N L, Zhao B, Pan J W 2012 *Nat. Phys.* **8** 517
- [20] Zhang S, Chen J F, Liu C, Zhou S, Loy M M, Wong G K, Du S 2012 *Rev. Sci. Instrum.* **83** 073102
- [21] Yang S J, Wang X J, Li J, Rui J, Bao X H, Pan J W 2015 *Phys. Rev. Lett.* **114** 210501

Experimental study of retrieval efficiency of Duan-Lukin-Cirac-Zoller quantum memory by optical cavity-enhanced*

Ma Teng-Fei¹⁾²⁾ Wang Min-Jie¹⁾²⁾ Wang Sheng-Zhi¹⁾²⁾ Jiao Hao-Le¹⁾²⁾

Xie Yan¹⁾²⁾ Li Shu-Jing^{1)2)†} Xu Zhong-Xiao¹⁾²⁾ Wang Hai¹⁾²⁾

1) (State Key Laboratory of Quantum Optics and Quantum Optics Devices,
Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China)

2) (Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan 030006, China)

(Received 10 May 2021; revised manuscript received 24 September 2021)

Abstract

Long-distance entanglement distribution is an important task for quantum communication, but difficult to achieve due to the loss of photons in optical fiber transmission. Quantum repeater is a scheme to solve this problem. In this scheme, the long distance of entanglement distribution is divided into several small parts, the entanglement is established first at both ends of each part, then, the entanglement distance is extended through the entanglement exchange of adjacent interval parts, in order to achieve the long distance entanglement distribution. Of them, the Duan-Lukin-Cirac-Zoller (DLCZ) protocol based on the cold atom ensemble and the linear optics which can generate and store entanglement, is regarded as one of the most potential schemes. In the process of DLCZ, retrieval efficiency is an important index of the quantum repeater, because it will influence each entanglement exchange operation between adjacent quantum repeater nodes. Generally, the retrieval efficiency is improved by optimizing the reading pulse, increasing the optical depth (OD) of the atomic ensemble and the cavity enhancement. The ring cavity constrains the light field to increase the intensity of the interaction between light and atoms, and effectively improve the retrieval efficiency of the quantum memory.

In this work, atomic ensembles are placed in a ring cavity. The cavity length is 3.3 m and the fineness is 13.5. The optical loss of all ring cavity is 21%, mainly including 15% loss of other optical elements and 6% loss of the cell. In order to increase the retrieval efficiency, we need to ensure the mode resonance of read-out photon, write-out photon and locking. The cavity needs two input beams of light: one comes from the path of read-out photon and the other from the path of write-out photon in the reverse direction. The two beams are locked at the same frequency as the write-out photon and the read-out photon respectively. The cavity length is adjusted by moving the cavity mirrors' positions through translating the frame, to make two light modes resonate. The acousto-optic modulator (AOM) is inserted into the path of the locking to control the frequency of the locking. By adjusting the AOM to change the frequency of the locking, the locking can be coincident with the write-out and read-out cavity modes. Then, the three-mode resonance can be achieved

When the cavity mode resonates with the atomic line, it will lead the atomic formants to split. thereby affecting the enhancement effect of retrieval efficiency. In the experiment, the detuning of the read light will affect the frequency of the read-out photon, and further affect the detuning of the cavity mode with the resonance line of the atom. Thus, by increasing the detuning between the reading light and the atomic transition line, the frequency splitting between the two modes can be reduced, then enhance the retrieval efficiency. We study the relation between the enhancement factor of the retrieval efficiency and the detuning amount of the reading light relative to the atomic resonance line. The results show that when the detuning amount of reading light is 80 MHz, the intrinsic readout efficiency is 45%, and the readout efficiency is enhanced by 1.68 times.

Keywords: quantum memory, retrieval efficiency, optical ring cavity

PACS: 03.67.-a, 03.67.Bg, 03.65.Ud

DOI: 10.7498/aps.71.20210881

* Project supported by the National Basic Research Program of China (Grant No. 2016YFA0301402), the National Natural Science Foundation of China (Grant Nos. 11475109, 11974228, 11604191), and the Shanxi Provincial Fund for "1331 Project" Key Subjects Construction, China (Grant No. 1331KSC).

† Corresponding author. E-mail: lishujing@sxu.edu.cn