An introduction to quantum networks

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Contents

- Introduction
- Solid-state quantum memory
- Summary

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- **Introduction**
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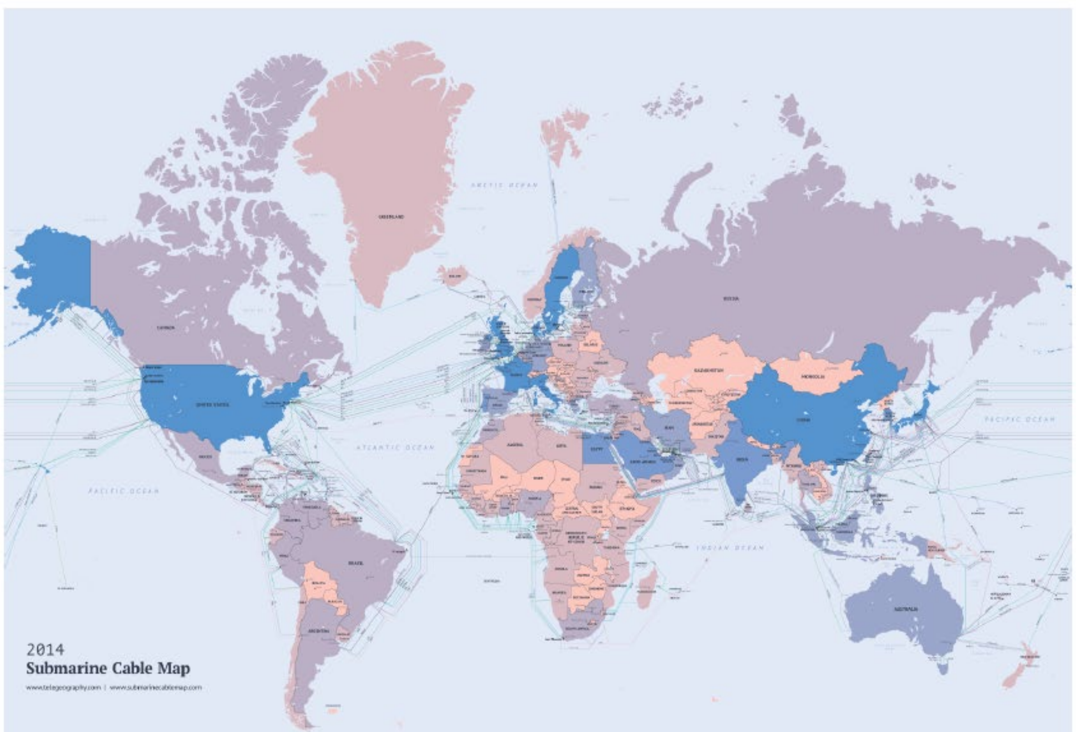
- **Summary**

Memory

- Memory: A medium for storage of information.
- Memories:

Classical communication

- Bit value (0 or 1) for encoding information.
- Strong laser pulse propagating along fiber.

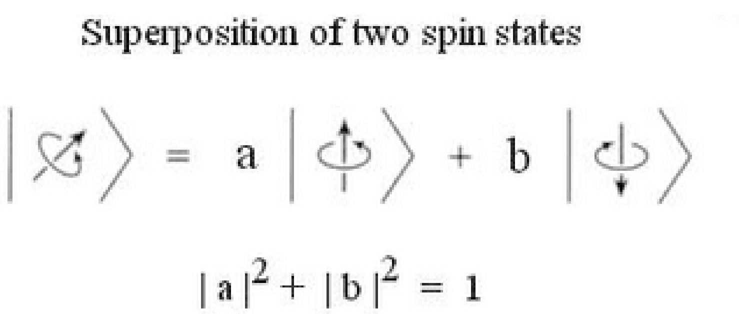


2014 全球海底光缆分布图

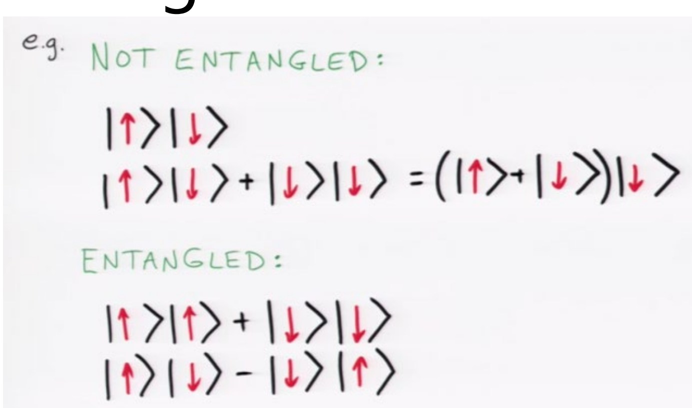
2009 Nobel Laureate
Charles Kao

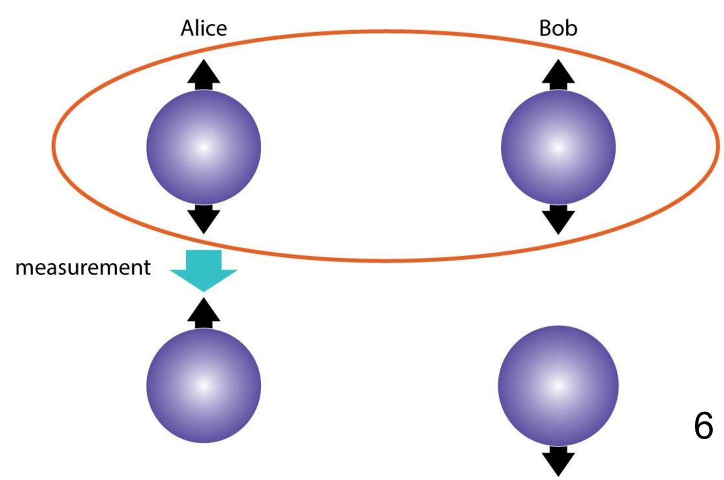
Quantum mechanics

- Weird quantum world：
  - Superposition



  - Entanglement

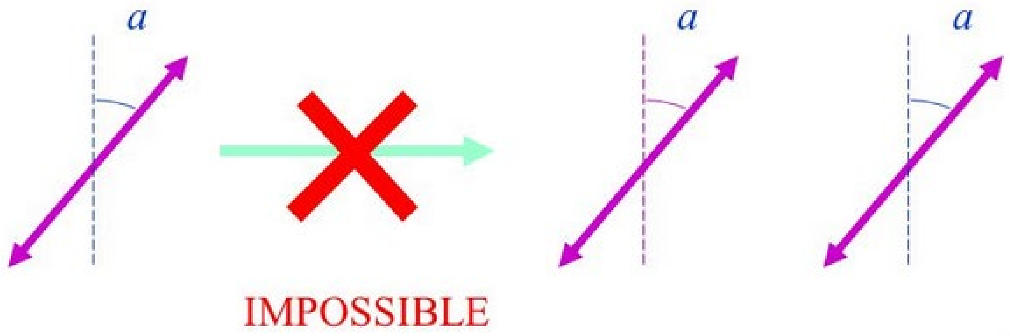




Quantum communication

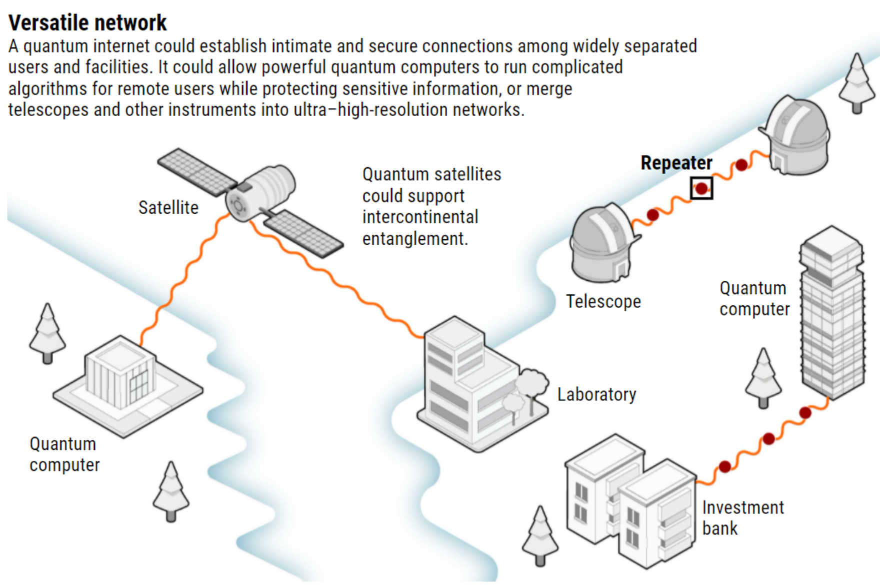
- Advantages:
  - The quantum information is carried by single photons which can not be divided or replicated.
  - Security based on quantum theory rather than computation complexity.

Qubit



Quantum Networks

- 1. Quantum key distribution: transfer of classical bit using single photons
- 2. Memory-based networks: transfer of entangled photons
- 3. Distributed quantum computing and sensing



N. DESAI/SCIENCE

Global quantum network?

- Challenges:

  - Exponential photon loss in fiber channels.
  - Cloning or amplifying is not allowed.

Photon rate:

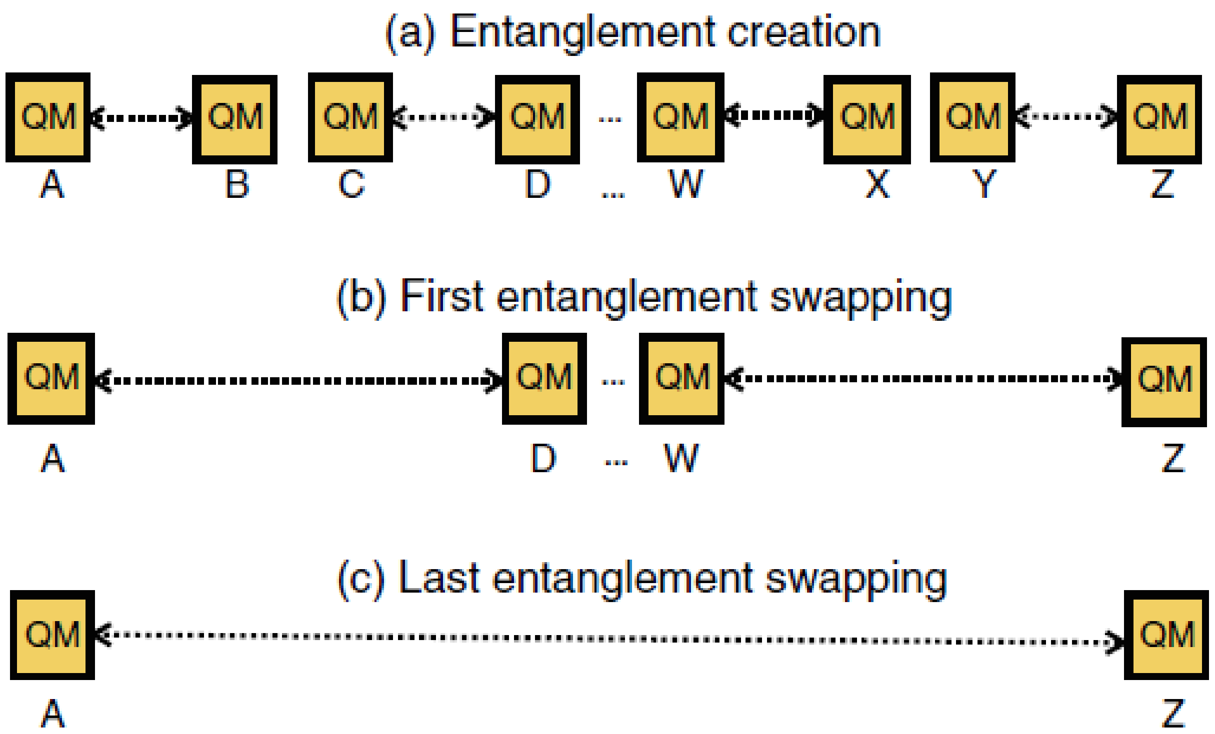
	10GHz →	**9.5GHz** →	**1Hz** →	**10^{-10}Hz**
Fiber length:		**1km**	**500km**	**1000km**

↓

One photon in 300 years!

Memory based quantum network

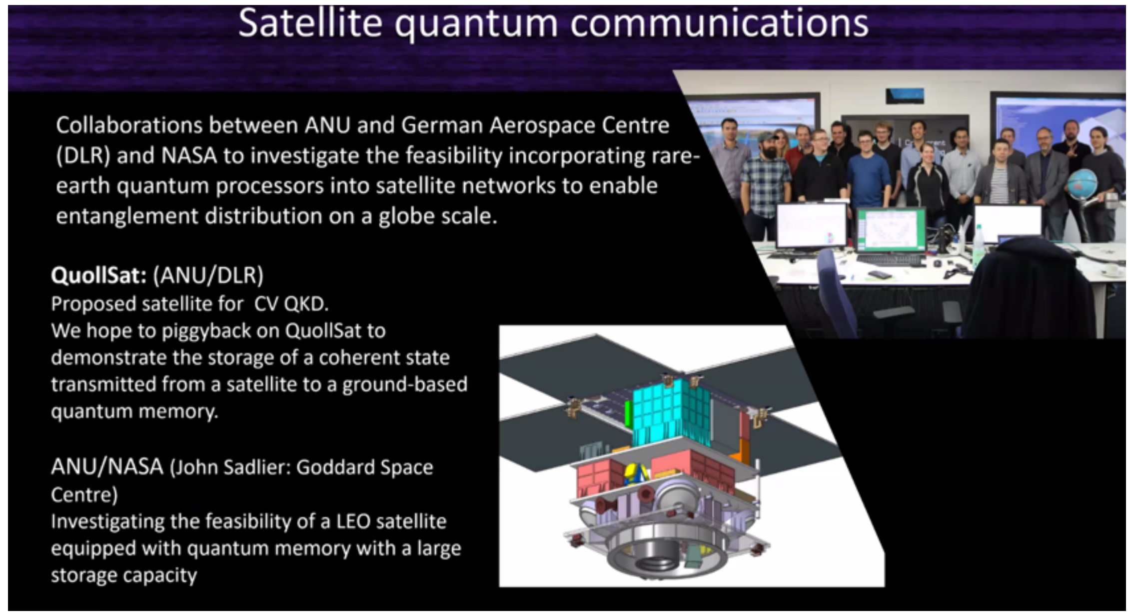
- Quantum repeater: divide and conquer

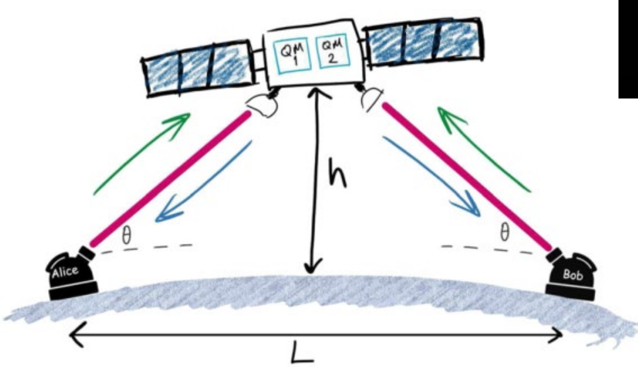


Gisin's group, Rev. Mod. Phys. 83.33 (2011)

Memory based quantum network

- Quantum repeater with free space channel





Proposal for space-borne quantum memories for global quantum networking

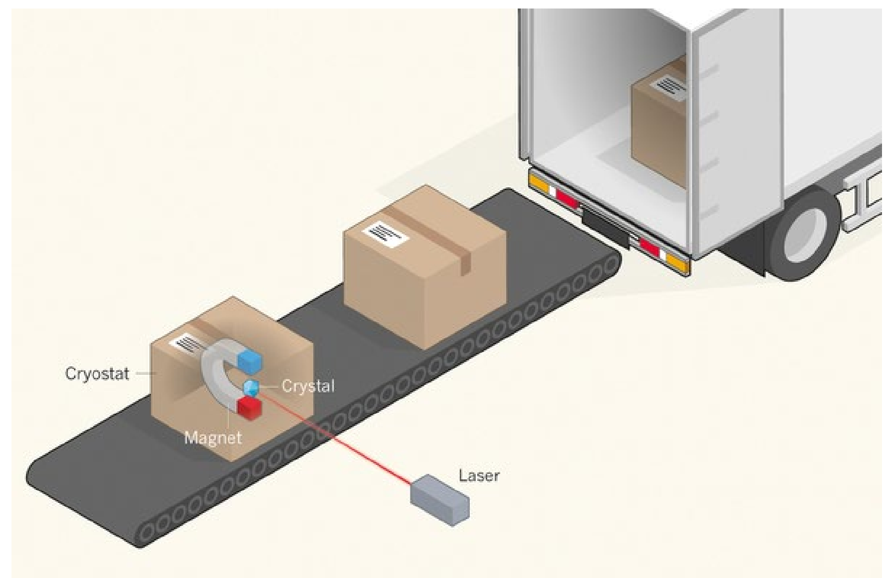
Mustafa Gündoğan, Jasminder S. Sidhu, Victoria Henderson, Luca Mazzarella, Janik Wolters, Daniel K. L. Oi & Markus Krutzik

npj Quantum Information **7**, Article number: 128 (2021) | Cite this article

Memory based quantum network

- Transportable quantum memories : classical transportation of quantum information

Amazon Snowmobile

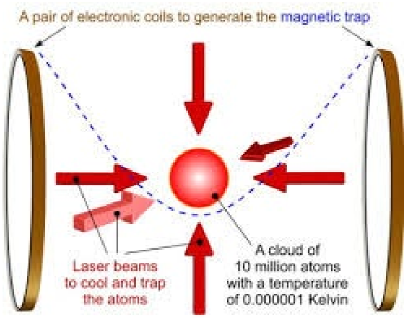


Sellars's group, Nature 517.153 (2015)

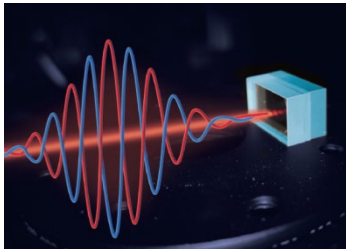
Quantum memory

- QM: coherent memory for photonic quantum states
- Physical systems for QM:

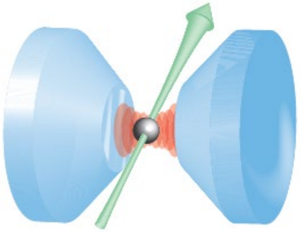
➢ Cold atoms / Room temperature atoms



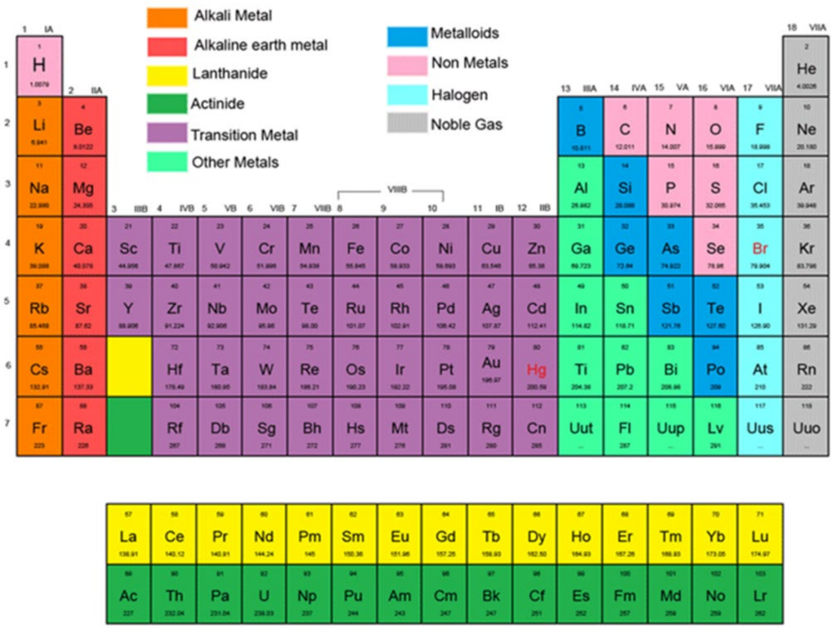
➢ Rare-earth-ion doped crystal

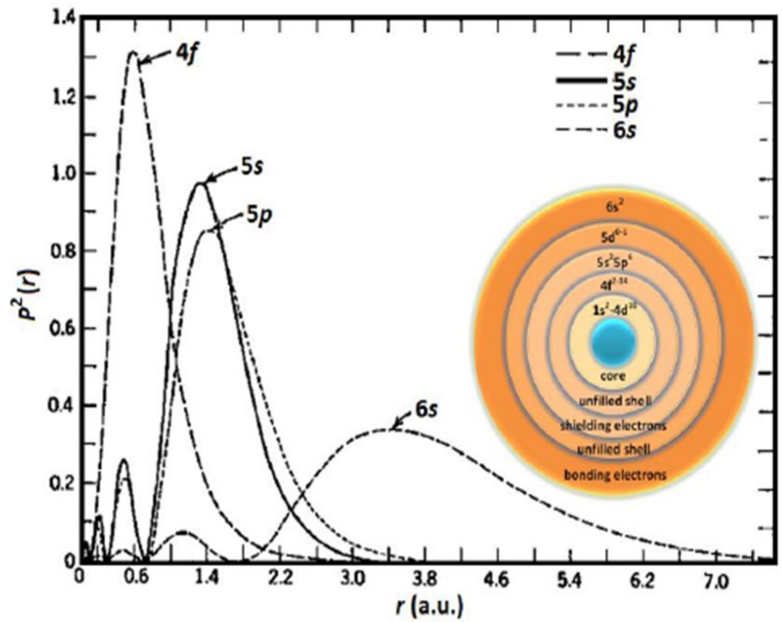


➢ Single atom…



Rare-earth ions





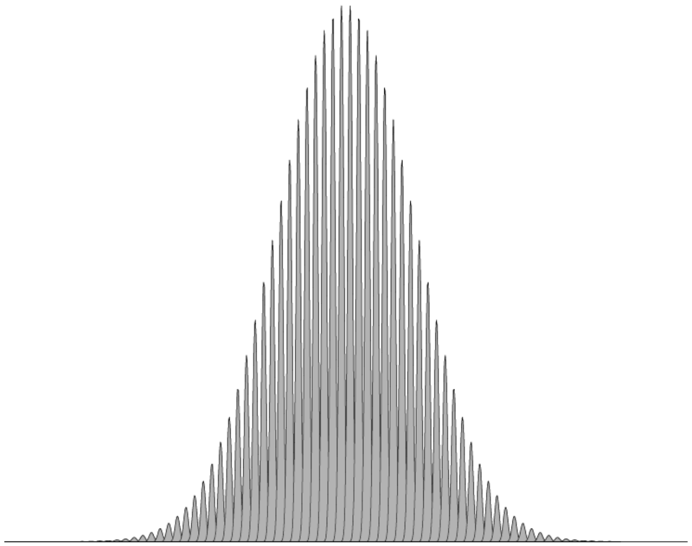
- Coherent 4f-4f transitions of RE^{3+}

➢ RE ions are successful laser medium --- light emission

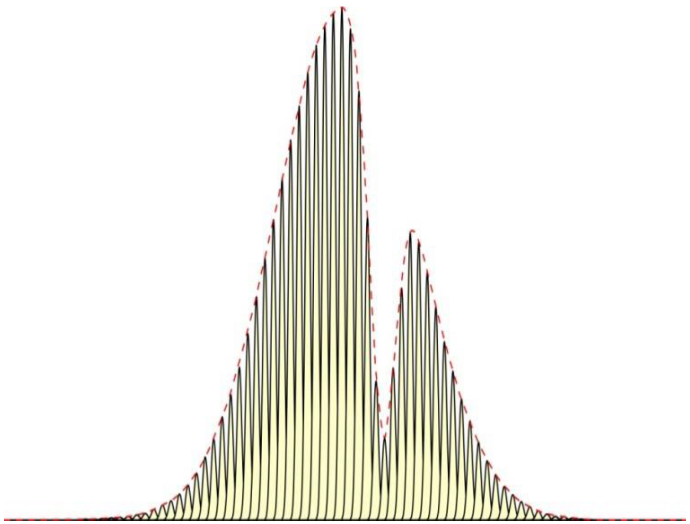
➢ We use them to store light --- light absorption

Rare-earth ions

- Due to the imperfect crystal lattice, RE ensemble has a large inhomogeneous broadening
- The inhomogeneous absorption profile can be arbitrarily tailored for the implementation of certain quantum storage protocols



Large inhomogeneous broadening

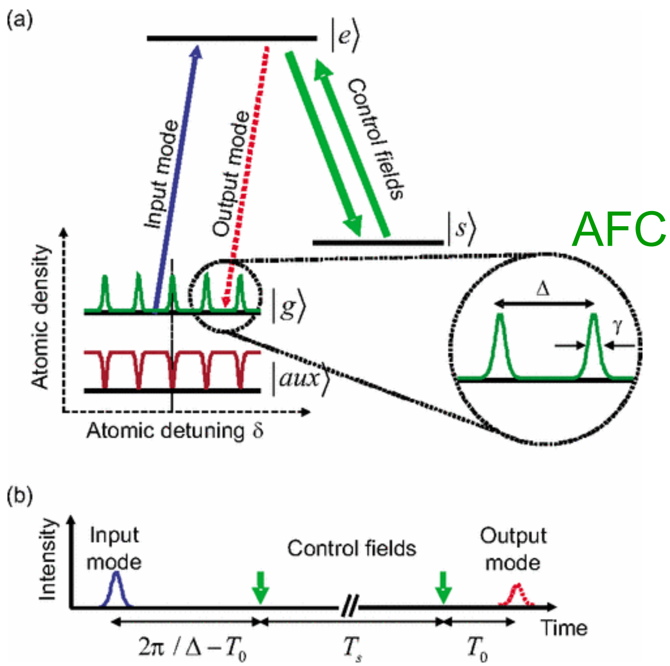


Spectral hole burning

AFC

- Memory protocols
- Atomic frequency comb (AFC)

- Spectral tailoring required
- Wide bandwidth and large multimode capacity
- Predetermined storage time with two-level AFC
- On-demand storage with spin-wave AFC



Afzelius et al., PRA 79, 052329 (2009)
de Riedmatten et al., Nature 456, 773 (2008)

Quantum memory

- Figure of merits for QM：
  - Fidelity
  - **Efficiency**
  - **Bandwidth**
  - **Storage time**
  - Multimode capacity
  - Integration
  - Wavelength, cost, stability…

Efficiency, Bandwidth, Storage time → Efficiency-time-bandwidth product (η*TBP):
Effective acceleration for communication

Challenges

- Quantum repeater approach:

➢ Requiring QM with good overall performances

➢ Higher data rate

- Transportable quantum memory approach:

➢ Requiring QM with:

✓ Extremely long lifetime

✓ High efficiency

✓ Integrated operations

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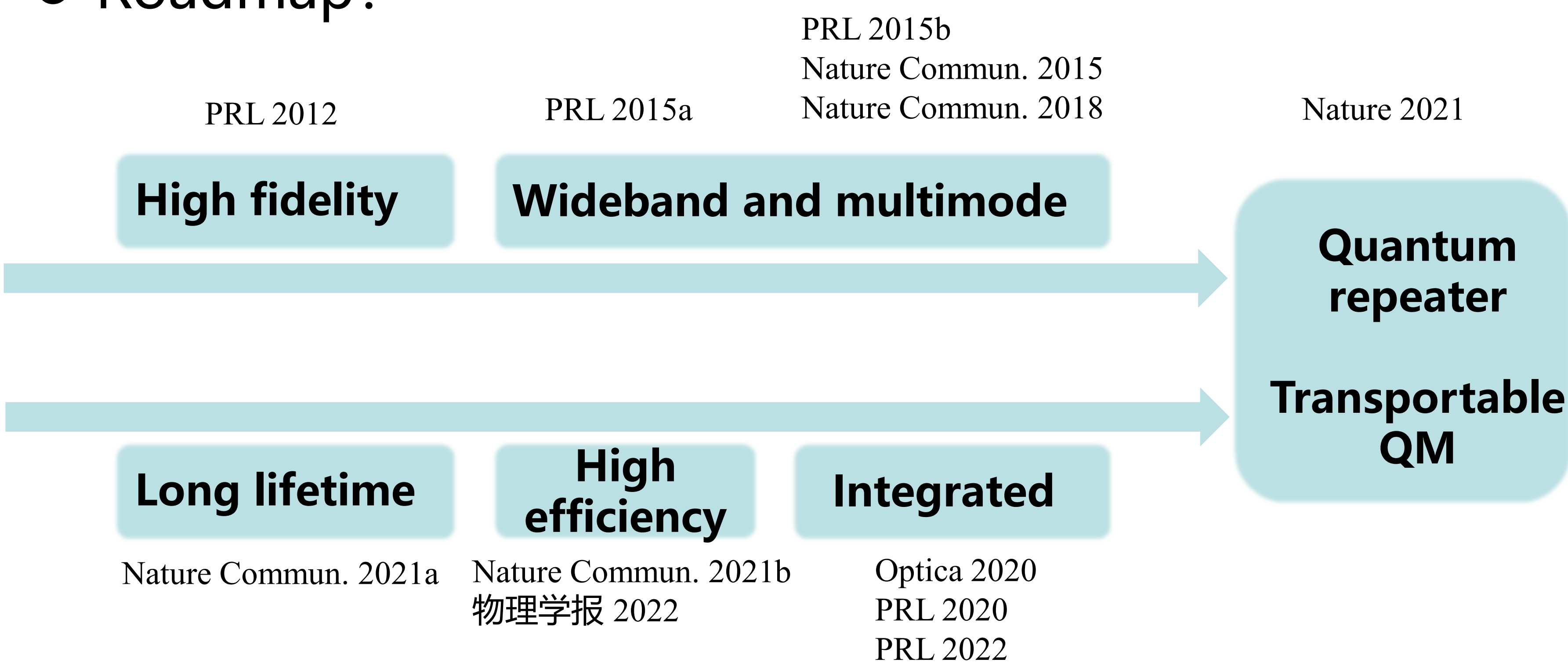
Solid-state quantum memory

- QM based on rare-earth ion doped crystal
- Roadmap：



Solid-state quantum memory

QM based on rare-earth ion doped crystal

PRL 2012
High fidelity

PRL 2015a
PRL 2015b
Nature Commun. 2015
Nature Commun. 2018
Wideband and multimode

Long lifetime
Nature Commun. 2021a

High efficiency
Nature Commun. 2021b
物理学报 2022

Integrated
Optica 2020
PRL 2020
PRL 2022

Nature 2021
Quantum repeater

Transportable QM

Solid-state quantum memory

QM based on rare-earth ion doped crystal

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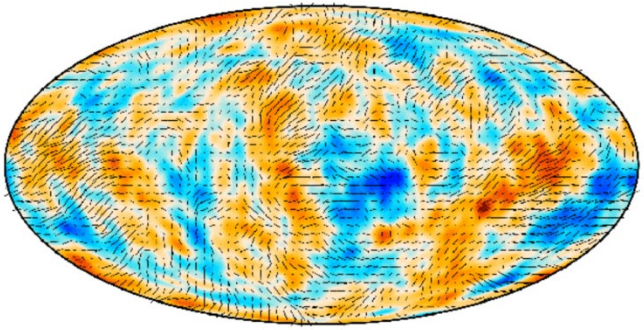
物理学报 2022

Integrated

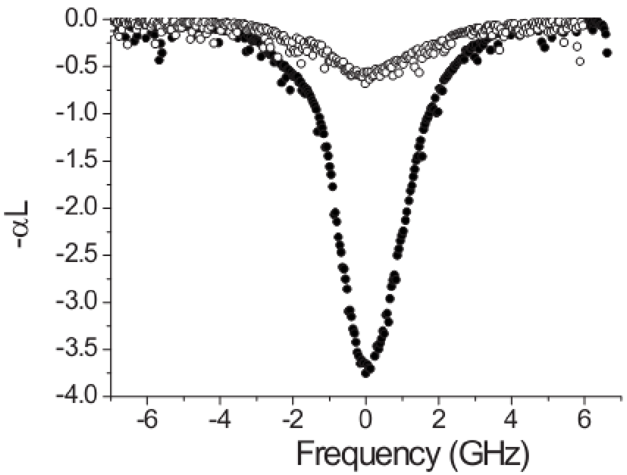
Optica 2020
PRL 2020
PRL 2022

High fidelity storage

- Radiation from the Big Bang is still partially polarized.
- Solid-state QM only works for a single polarization while superposition polarization states are required in quantum communication
- Challenge: polarization-dependent absorption for solids



CMB , Planck Satellite, 2015



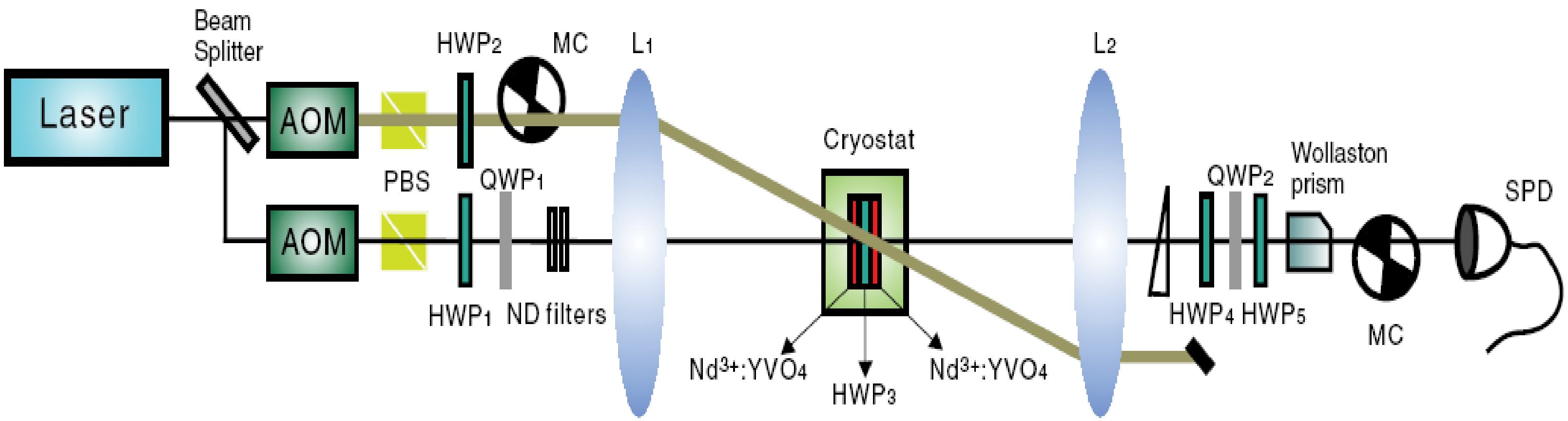
Gisin's group, PRB(2008) Single piece of Nd:YVO

High fidelity storage

☐ Solutions: Sandwich-like structure

- ➢ Uniform absorption
- ➢ The first solid-state QM for polarization
- ➢ Fidelity up to 99.9(2)%

Two pcs of Nd:YVO, 10x10x1.4mm, sandwiching one half-wave plate.



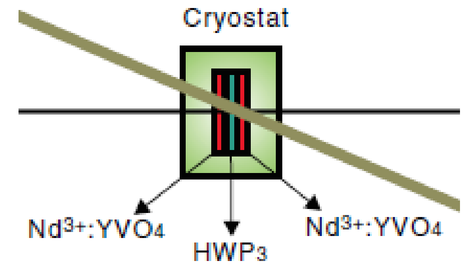
Z.-Q. Zhou, et al., Phys. Rev. Lett. 108, 190505 (2012)
High lighted by APS Physics and Physics World

High fidelity storage

PRL **108,** 190505 (2012) PHYSICAL REVIEW LETTERS week ending 11 MAY 2012

Realization of Reliable Solid-State Quantum Memory for Photonic Polarization Qubit

Zong-Quan Zhou, Wei-Bin Lin, Ming Yang, Chuan-Feng Li,* and Guang-Can Guo

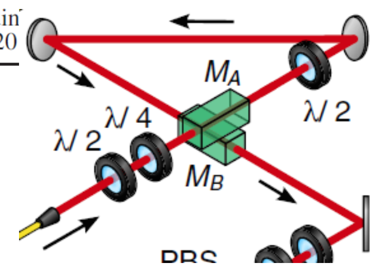


Fidelity of 99.9%

PRL **108,** 190503 (2012) PHYSICAL REVIEW LETTERS week endin 11 MAY 20

Quantum Storage of Heralded Polarization Qubits in Birefringent and Anisotropically Absorbing Materials

Christoph Clausen, Félix Bussières, Mikael Afzelius,* and Nicolas Gisin

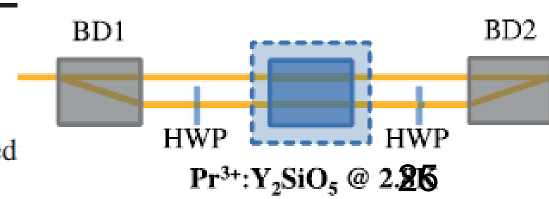


Fidelity of 97.5%

PRL **108,** 190504 (2012) PHYSICAL REVIEW LETTERS week ending 11 MAY 2012

Quantum Storage of a Photonic Polarization Qubit in a Solid

Mustafa Gündoğan,[1,*] Patrick M. Ledingham,[1] Attaallah Almasi,[1,†] Matteo Cristiani,[1] and Hugues de Ried

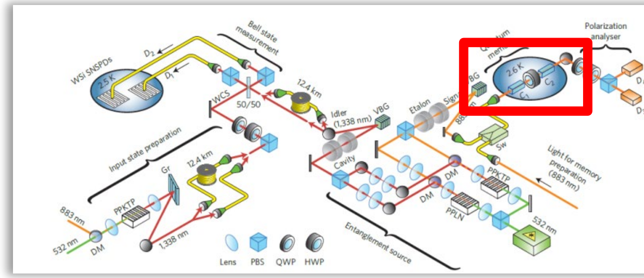


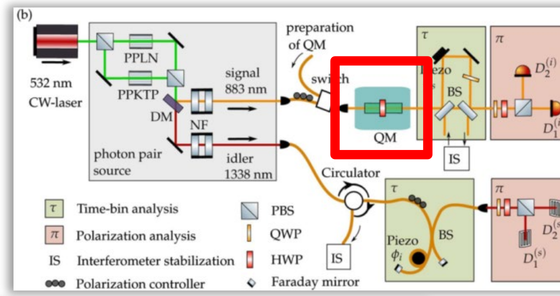
Fidelity of 95%

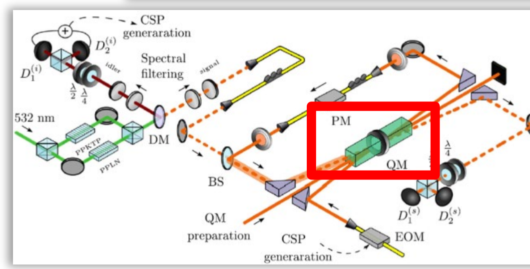
High fidelity storage

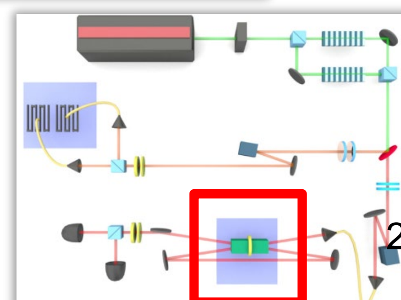
Sandwich-like design is employed by N. Gisin's group:

1. Teleportation using QM [Nature Photonics 8, 775 (2014)];
2. QM for hyper-entanglement [Optica 2, 279 (2015)];
3. Micro-macro entanglement between light and matter [PRL 116, 190502 (2016)];
4. Multimode QM for polarization entanglement [PRL 117, 240506 (2016)];
5. Multimode spin-wave storage of polarization [New J. Physics 18, 013006(2016)];









High fidelity storage

Prospective applications of optical quantum memories

Félix Bussières[a], Nicolas Sangouard[a], Mikael Afzelius[a], Hugues de Riedmatten[bc], Christoph Simon[d] & Wolfgang Tittel[d]

Journal of Modern Optics

Volume 60, Issue 18, 2013

In part triggered by the improved understanding of necessary properties, and in part causing it, impressive progress in the storage and recall of quantum states in atomic ensembles and individual absorbers has been achieved over the last few years. This includes storage efficiencies of up to 87% [35,36], storage over 5 GHz bandwidth [34], simultaneous storage of several temporal modes [37,38], readout fidelities exceeding 99% [39], the combination of high efficiency (73%) and long storage time (3 ms) [40], and storage and

[39] Zhou, Z.Q.; Lin, W.B.; Yang, M.; Li, C.F.; Guo, G.-C. *Phys. Rev. Lett.* **2012**, *108*, 190505.

Solid-state quantum memory

QM based on rare-earth ion doped crystal

PRL 2012

High fidelity

PRL 2015a

PRL 2015b
Nature Commun. 2015
Nature Commun. 2018

Wideband and multimode

Nature 2021

Quantum repeater

Transportable QM

Long lifetime

Nature Commun. 2021a

High efficiency

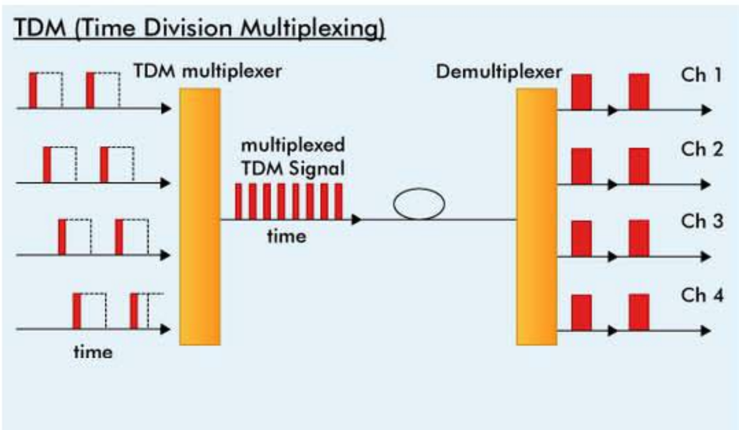
Nature Commun. 2021b
物理学报 2022

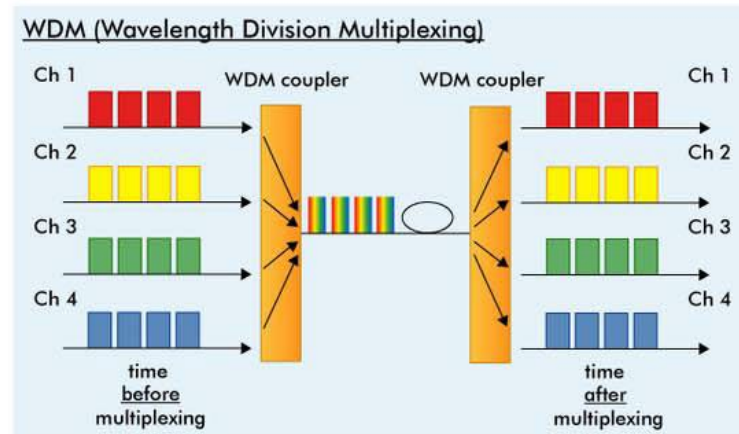
Integrated

Optica 2020
PRL 2020
PRL 2022

Wideband and Multimode

- Multiplexing (TDM, WDM) are key tools for enhancing the data rate in classical communications





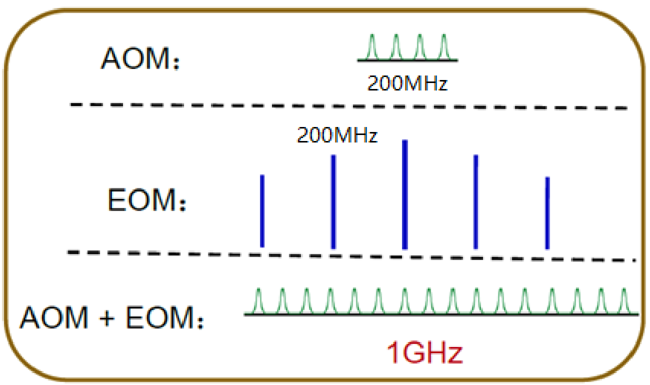
- Tb/s with Orbital angular momentum (OAM) and polarization multiplexing in vortex fibers

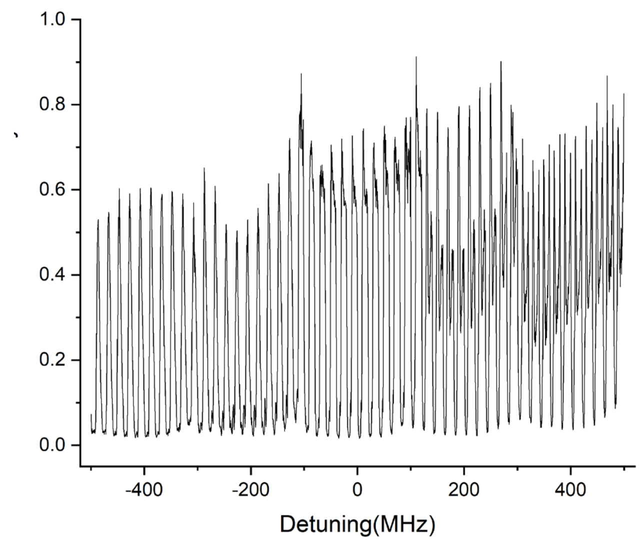
Science AAAS

Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers
Nenad Bozinovic *et al.*
Science **340**, 1545 (2013);
DOI: 10.1126/science.1237861

Wideband and Multimode

- Bandwidth is the key resource for multiplexing
- Bandwidth limited by the medium and the pump light
- Extended to 1 GHz using acoustic-optic and electro-optic modulations (AOM & EOM)





目前存储效率 ~20%@900MHz

对比Gisin's group: ~5%@600MHz [Nature Photon. 8, 775 (2014)]

Wideband and Multimode

- Analogue to techniques employed in classical communication, we multiplex our memory device using multiple degree of freedoms (DOF)

Performances	Novelties	Publications
Bandwidth	Acoustic-optic and electro-optic modulations for hole burning	**Z.-Q. Zhou**, Huelga, Li, Guo, PRL 115, 113002 (2015)
Time DOF	Deterministic photons from single quantum dots	J.-S. Tang#, **Zhou#,** et al., Nature Communications 6, 8652 (2015)
Spatial DOF	Orbital angular momentum (OAM)	**Z.-Q. Zhou**, Hua, et al., PRL 115, 070502 (2015)
Multiple DOF	Time & spectral & OAM	T.-S. Yang, **Zhou***, et al., Nature Communications 9, 3407 (2018)

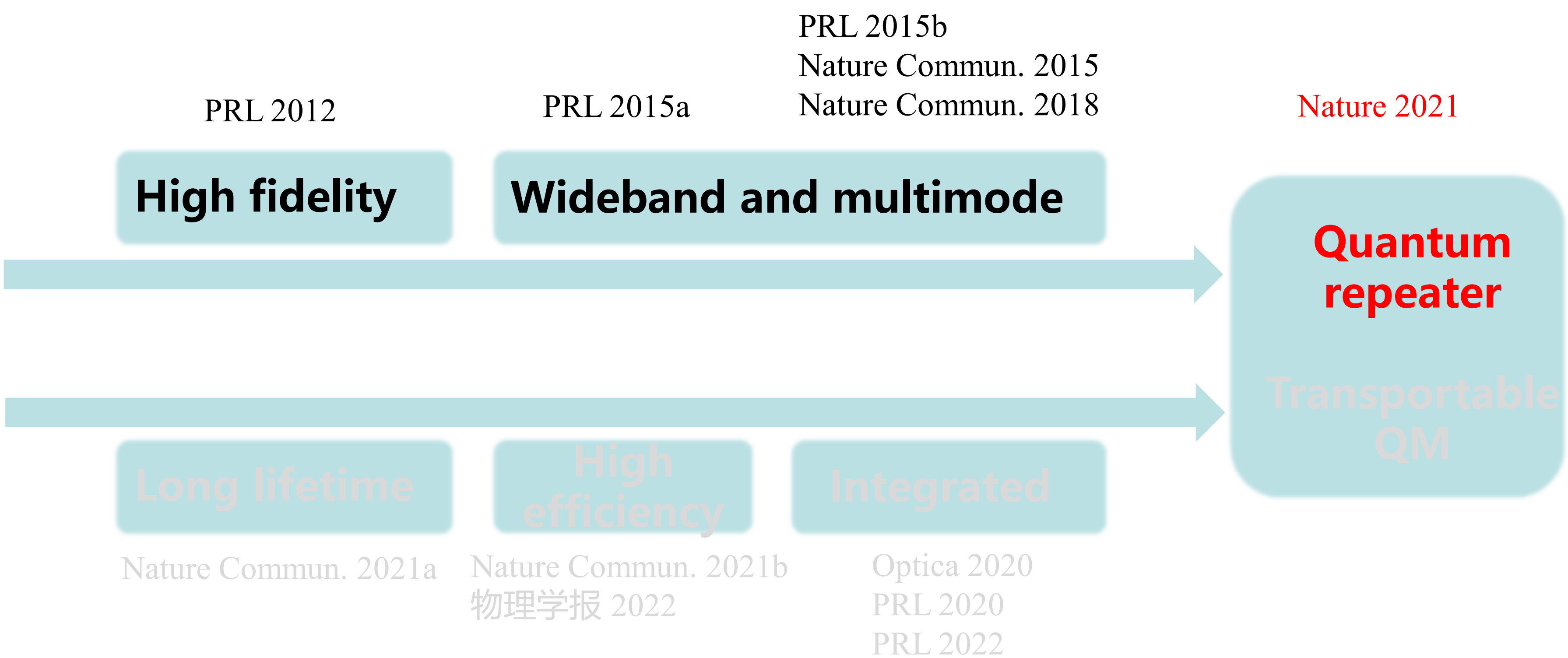
Overall performances

- Fidelity for polarization qubit storage: 99.9%
- Efficiency-time-bandwidth product (η*TBP): 7.8, the best result for wideband solid-state quantum memories
- Ready for a demonstration of quantum repeaters

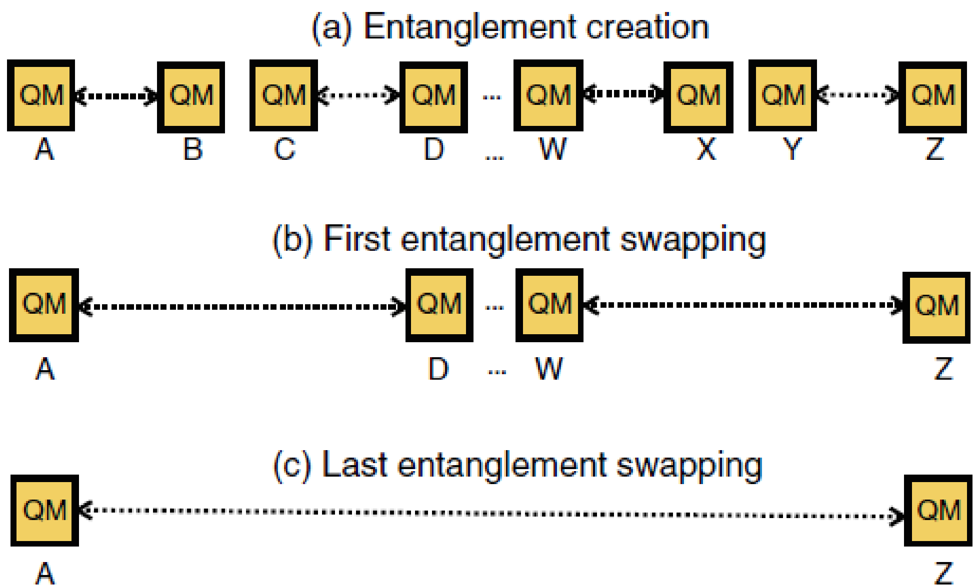
Efficiency η	Storage time T	Bandwidth B	η*TBP	Doped ions	Reference
14%	56 ns	1 GHz	7.8	Nd	Our work
5%	50 ns	0.6 GHz	1.5	Nd	N. Gisin, Nature Photonics 8, 775 (2014)
1%	15 ns	16 GHz	2.4	Er	W. Tittel, Nature Communication 7, 11202 (2016)
2%	31 ns	10 GHz	6.2	Tm	W. Tittel, PR Research 2, 013039 (2020)
7%	25 ns	1.6 GHz	2.8	Tm with cavity	W. Tittel, PRA 101, 042333 (2020)

Solid-state quantum memory

QM based on rare-earth ion doped crystal



Quantum repeater



- Basic operations of a quantum repeater
  - Entanglement creation in elementary links
  - Entanglement swapping between elementary links

Gisin's group, Rev. Mod. Phys. 83, 33 (2011)

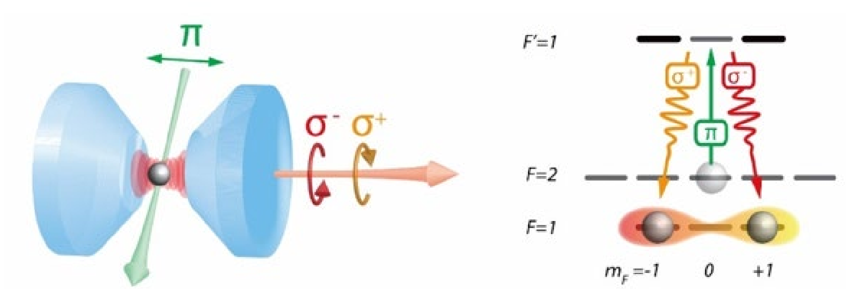
Quantum repeater

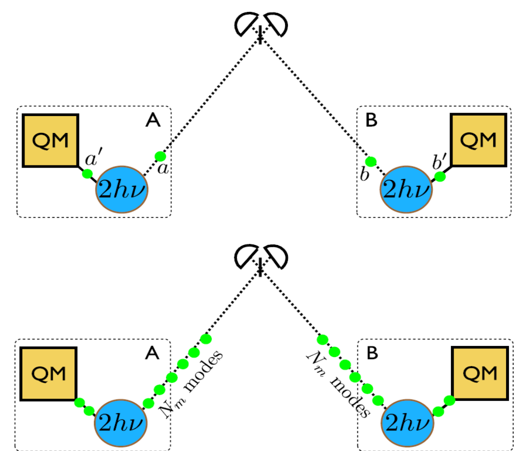
- How to enhance the entanglement distribution rate (EDR)?
  - The successful probability of photonic entanglement swapping is determined by the principle of quantum optics
  - Enhancing the rate of entanglement creation in an elementary link is the key tool that attracted intense research efforts

- Two limiting factors
  - 1, the emission efficiency of the photon source
  - 2, unavoidable losses caused by the transmission and imperfect devices

Quantum repeater

- Incompatible requirements
- ➢ 1, Efficiency of the photon source
- ✓ Using the deterministic photon source -- requires single-atom system
- ➢ 2, Unavoidable losses
- ✓ Using the multiplexed memory to overcome the losses -- requires atomic ensemble





An elementary link

- All previous demonstrations of quantum repeaters are based on the emissive QM

- Single-atom system: trapped ions, NV centers
- Deterministic photon emission but no efficient multiplexing

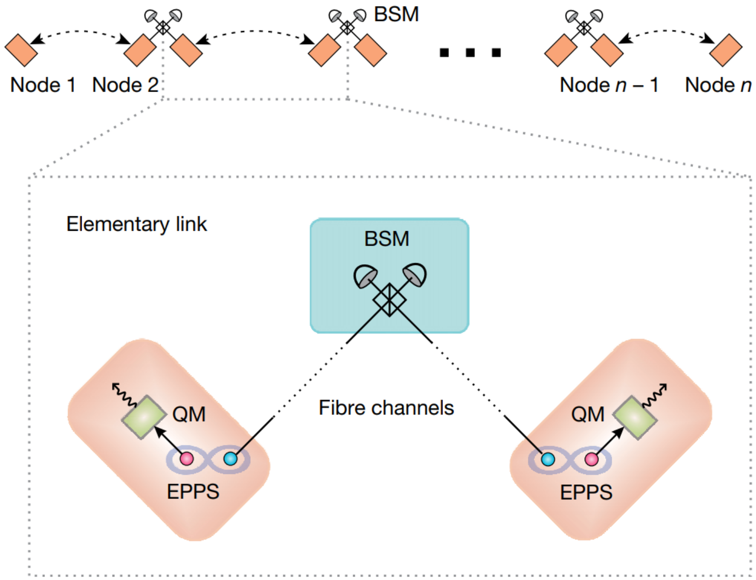
C. Monroe group, Nature 449, 68 (2007),
R. Hanson group, Nature 497, 86 (2013) ; Nature 526, 682 (2015)

- Emissive atomic ensemble: cold atoms
- Support multiplexing but intrinsically probabilistic emission

J. Kimble group, Science 316, 1316 (2007) ;
JW Pan group, Nature 454, 1098 (2008); Nature 578, 240 (2020)

Absorptive QM

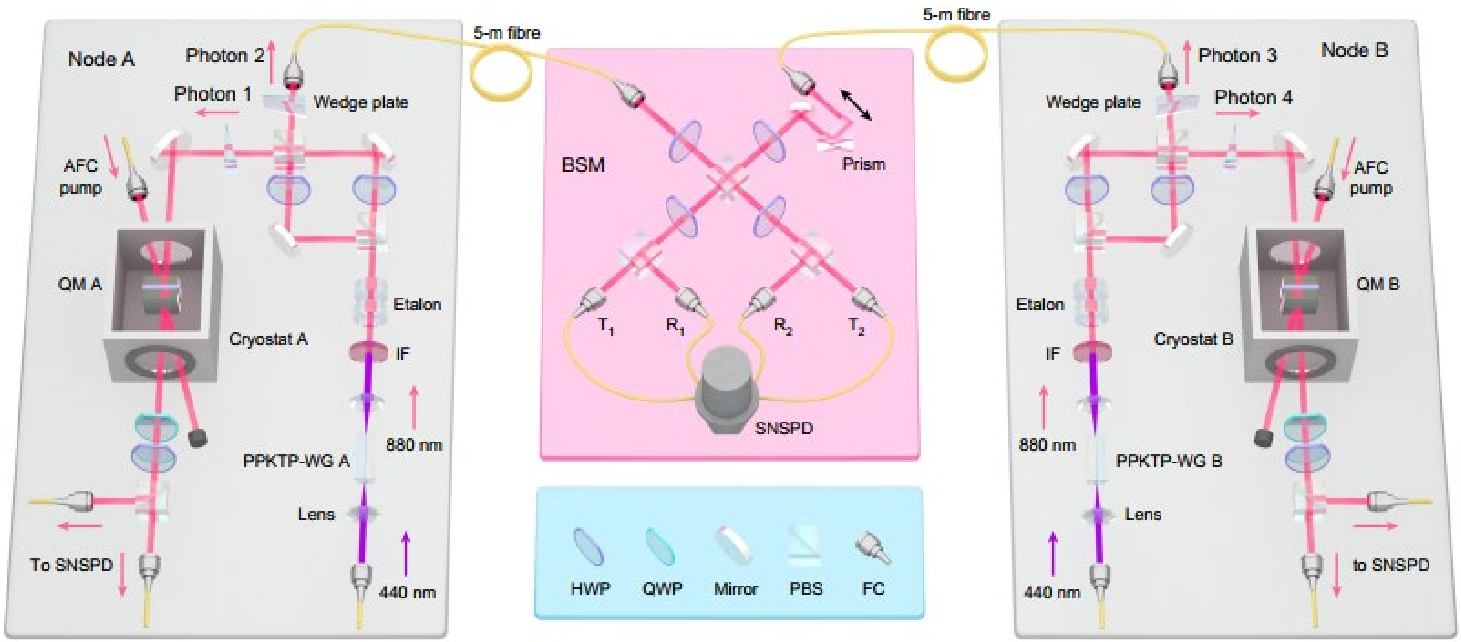
- The first quantum repeater based on absorptive QM
  - Ensemble memory: multimode
  - Compatible with single atom light source: deterministic



X. Liu#, Hu#, Li, Li, Li, Liang, **Zhou***, Li*, Guo, Nature 594, 41 (2021) ESI hot paper

Multimode quantum repeater

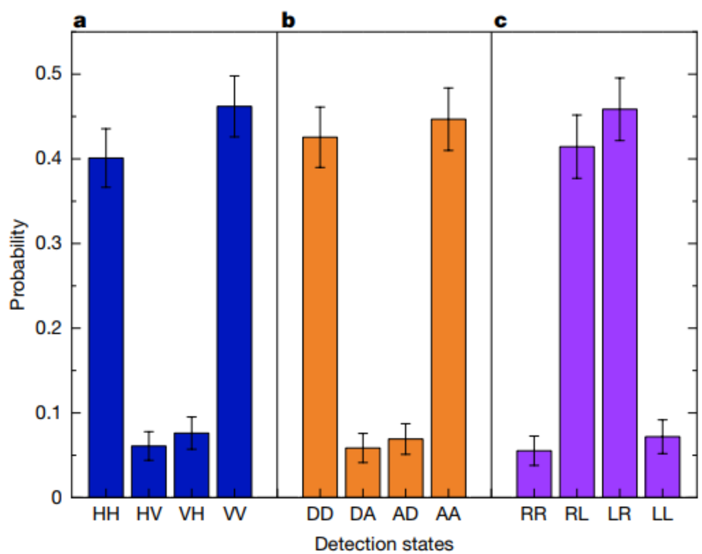
- Results
  - Sandwitch-like memories： η*TBP of 7.8
  - Waveguide based spontaneous parametric down-conversion



X. Liu#, Hu#, Li, Li, Li, Liang, **Zhou***, Li*, Guo, Nature 594, 41 (2021) ESI hot paper

Multimode quantum repeater

- Results
  - 4 temporal modes， 4 times enhanced data rate
  - Successful implementations of TDM to quantum repeaters



[redacted]

Fidelity： 80.4(2.2)%

X. Liu#, Hu#, Li, Li, Li, Liang**, Zhou***, Li*, Guo, Nature 594, 41 (2021) ESI hot paper

Multimode quantum repeater

IOP Publishing

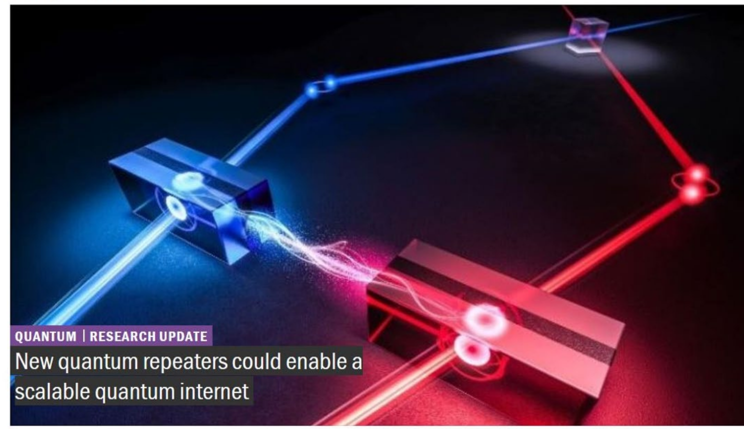
physicsworld

[Zhou Zongquan](#) at USTC says, "Our work shows a complete demonstration of an elementary link of a quantum repeater based on absorptive memories." On future developments he adds: "We will update the light source to a deterministic entanglement source to greatly enhance the entanglement distribution rate. Overall the performances of the memory should be greatly enhanced, including efficiency, lifetime and multimode capacity and be optimized according to the applications of a practical quantum repeater.'

"Important achievement"

Ronald Hanson at Delft University of Technology in the Netherlands is positive about both teams' achievements: "These results can be considered an important achievement in the specific context of building quantum repeaters, towards improved transmission of quantum communication over long distances. For solid-state ensemble-based memories, these push the state of the art significantly. Most important is the combination of operation

Today's headlines



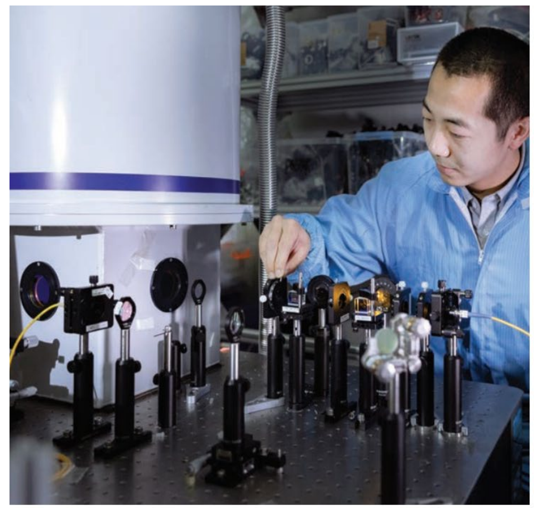
Multimode quantum repeater

Optics and Photonics News Vol. 33, Issue 4, pp. 34-41 (2022)

Edwin Cartlidge

How to Span the Quantum Gap

Building continental-scale quantum communications links is an arduous task, but scientists believe they have the technology in hand.



Zong-Quan Zhou, a scientist at USTC in Hefei, China, co-leads one of a number of teams around the world that have demonstrated components for a quantum repeater in the lab and that now plan to carry out field tests.
USTC News Center

The fiber optic cables that crisscross the world's oceans are studded every few tens of kilometers by repeaters—devices that compensate for the fibers' attenuation by boosting the power of a signal and retrans-

Yet progress is picking up pace. Backed by government programs aimed at realizing quantum networks, a number of groups are making the transition from proof-of-principle physics experiments to working devices. Indeed, Mikhail Lukin of Harvard University, USA, reckons that his group could field-test a prototype repeater within the coming year. "The main challenge now is working on the technology to be able to scale it up," he says. "But I wouldn't be surprised if in the next five years or so we are experimenting with systems that can do continent-scale communication."

No need for trust

One form of quantum communication, QKD, is already used in the real world. The principle here is that Alice (as

Solid-state quantum memory

QM based on rare-earth ion doped crystal

PRL 2012

High fidelity

PRL 2015a

PRL 2015b
Nature Commun. 2015
Nature Commun. 2018

Wideband and multimode

Nature 2021

Quantum repeater

Transportable QM

Long lifetime

Nature Commun. 2021a

High efficiency

Nature Commun. 2021b
物理学报 2022

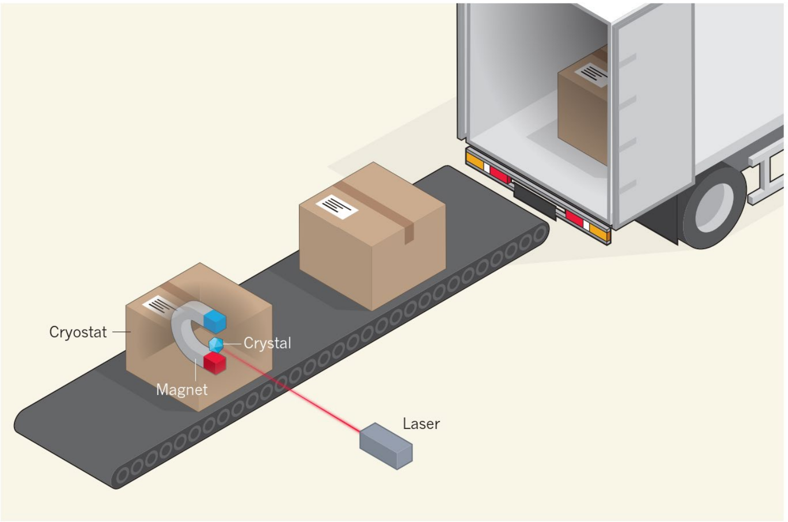
Integrated

Optica 2020
PRL 2020
PRL 2022

Transportable QM

- A new communication channel
- Required storage time of hours to days
- Extending the storage lifetime is equivalent to reducing the channel loss coefficient

Amazon Snowmobile
for classical data transmission



J. Morton & K. Molmer,
Nature 517, 153 (2015)

Storage of light

- Capture and storage of light
  - Two step, 1st： Slow light

Published: 18 February 1999

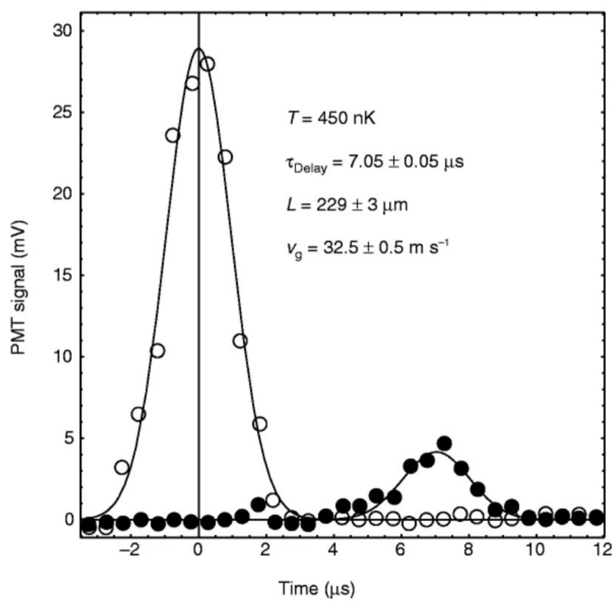
Light speed reduction to 17 metres per second in an ultracold atomic gas

Lene Vestergaard Hau, S. E. Harris, Zachary Dutton & Cyrus H. Behroozi

Nature **397**, 594–598(1999) | Cite this article

$v = c/n_g$

$L = v*t$



Spatial compressing of light into mm-scale medium

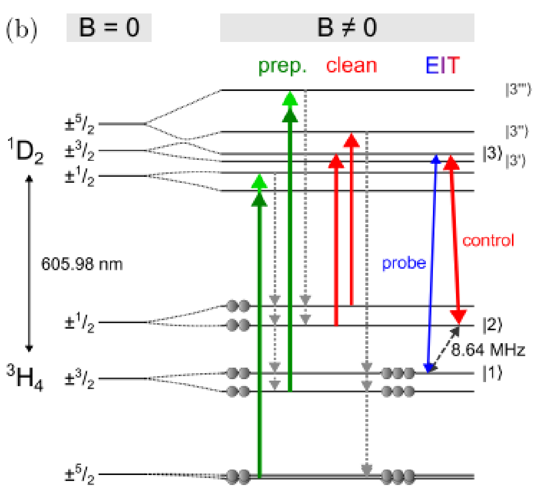
Long-lived storage of light

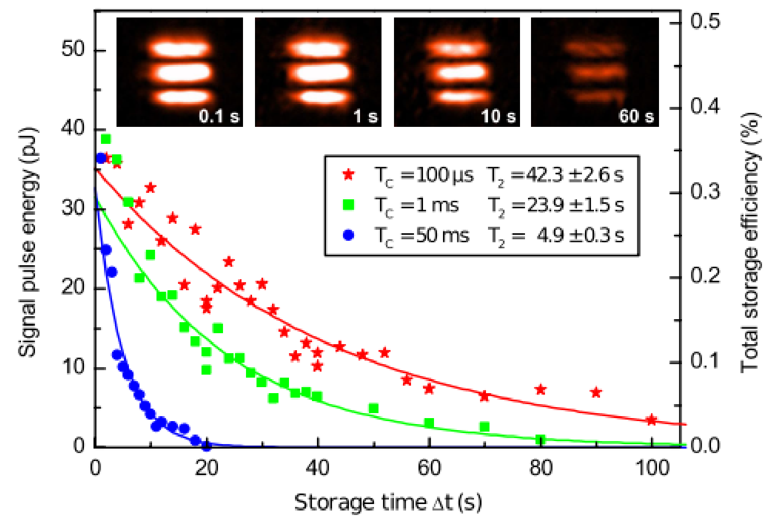
- ➢ 2nd： Stopped light （Spin excitations， v=0）
- ✓ 1 minute light storage demonstrated with Pr:YSO

Selected for a Viewpoint in *Physics*
PRL **111,** 033601 (2013) PHYSICAL REVIEW LETTERS week ending 19 JULY 2013

Stopped Light and Image Storage by Electromagnetically Induced Transparency up to the Regime of One Minute

Georg Heinze,* Christian Hubrich, and Thomas Halfmann†
Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstraße 6, 64289 Darmstadt, Germany





Pr:YSO

Image storage, lifetime approaching the T1 limits

Long-lived spin coherence

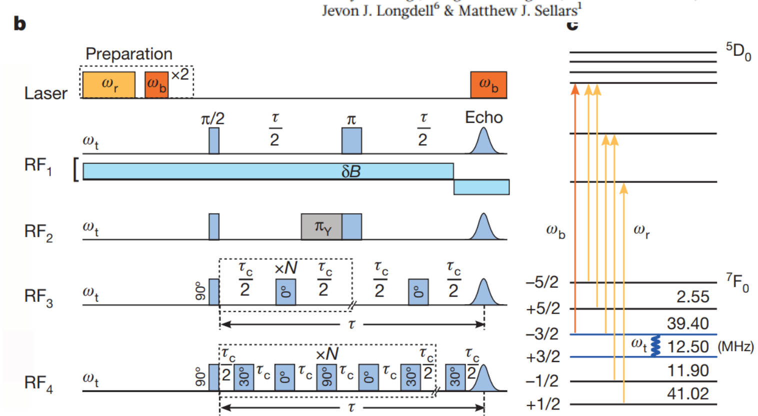
- Spin T_1 up to 1 month in Eu:YSO, spin T_2 (coherence time) up to 6 hours
- A candidate system for transportable QM
- Unresolved level structure, no light is stored

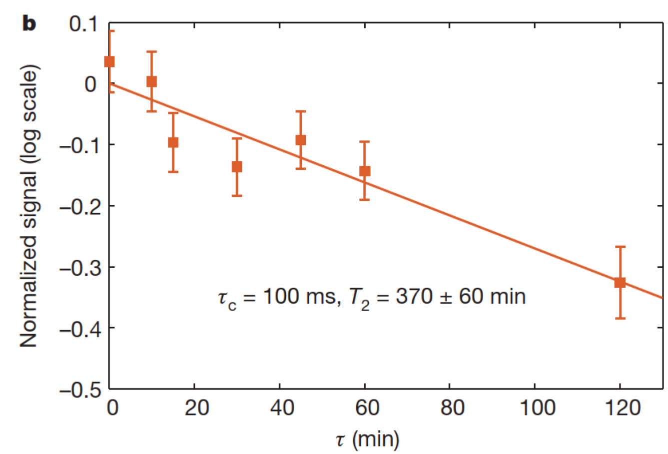
LETTER

doi:10.1038/nature14025

Optically addressable nuclear spins in a solid with a six-hour coherence time

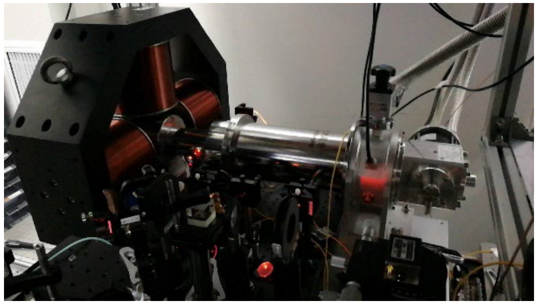
Manjin Zhong[1], Morgan P. Hedges[1,2], Rose L. Ahlefeldt[1,3], John G. Bartholomew[1], Sarah E. Beavan[1,4], Sven M. Wittig[1,5], Jevon J. Longdell[6] & Matthew J. Sellars[1]

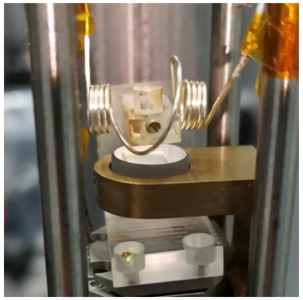


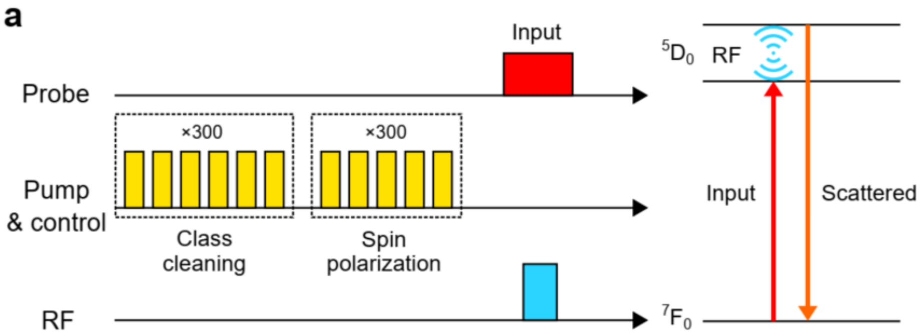


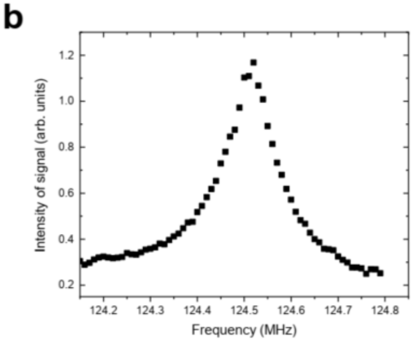
ZEFOZ field (clock transition) + dynamical decoupling (DD)

- c.w. Raman heterodyne NMR for characterization of the spin Hamiltonian, predicting level structure at ZEFOZ
- Pulsed NMR for accurate and direct measurements at the ZEFOZ field







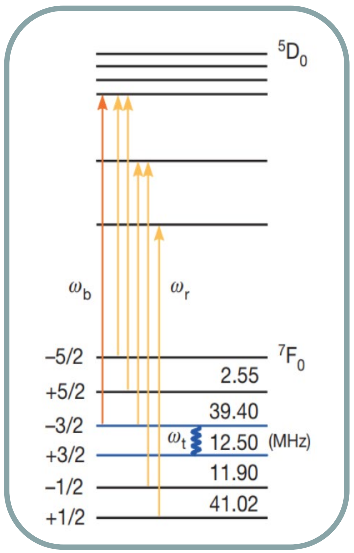


Y. Ma, et al, J. of Lumin. 202. 32 (2018),
Y. Ma, et al, Nature Commun. 12. 2381 (2021)

Level structure

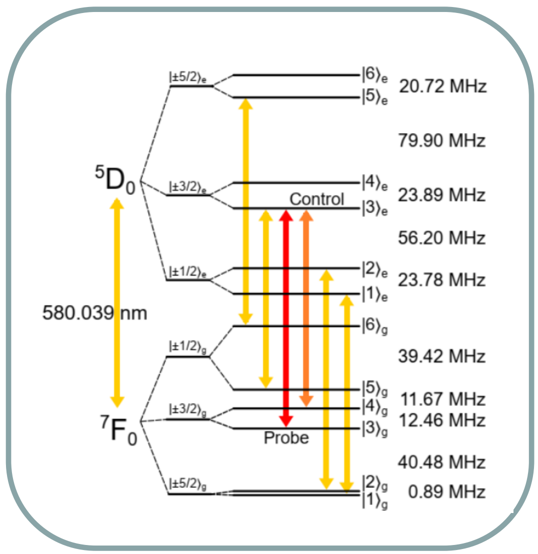
- Cw Raman-heterodyne-detected NMR，predictions on the structure
- Pulsed NMR，determining the level structure @ ZEFOZ

$$H = B\cdot M\cdot I + I\cdot Q\cdot I,$$

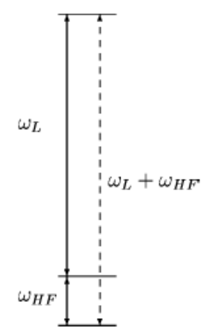


M. Sellars group
Nature 2015

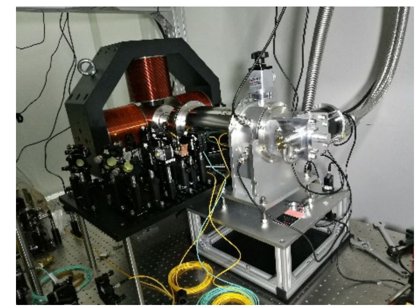
→

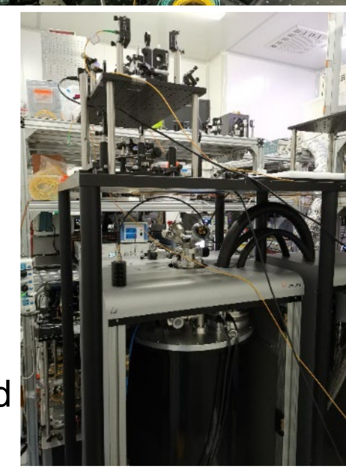


Our group
NC 2021



Raman-detected NMR



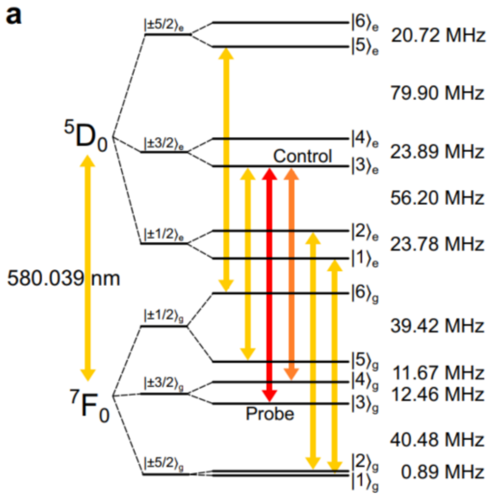


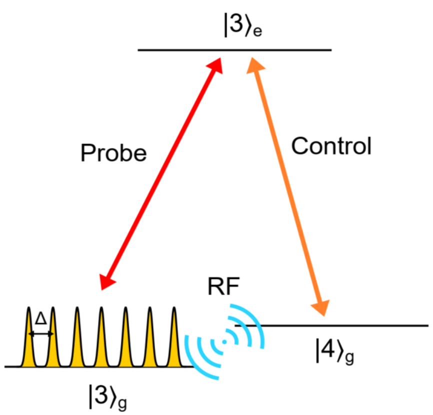
Patent: 201711126532.X

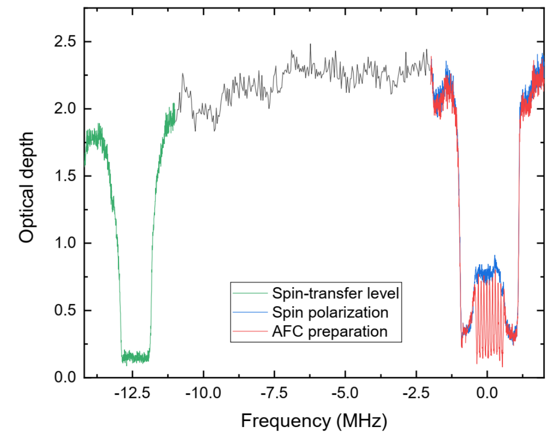
Y. Ma, Ma, Zhou*, Li*, Guo, Nature Commun. 12, 2381 (2021)

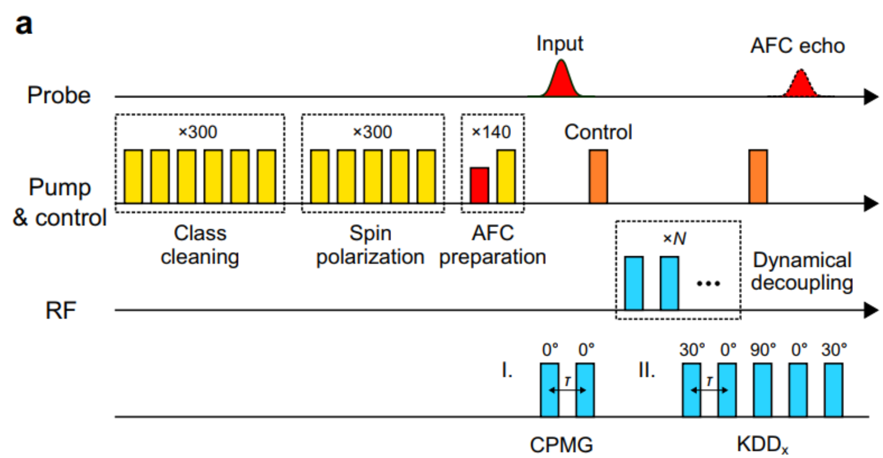
1-hour coherent optical storage

- Spin AFC + ZEFOZ + DD





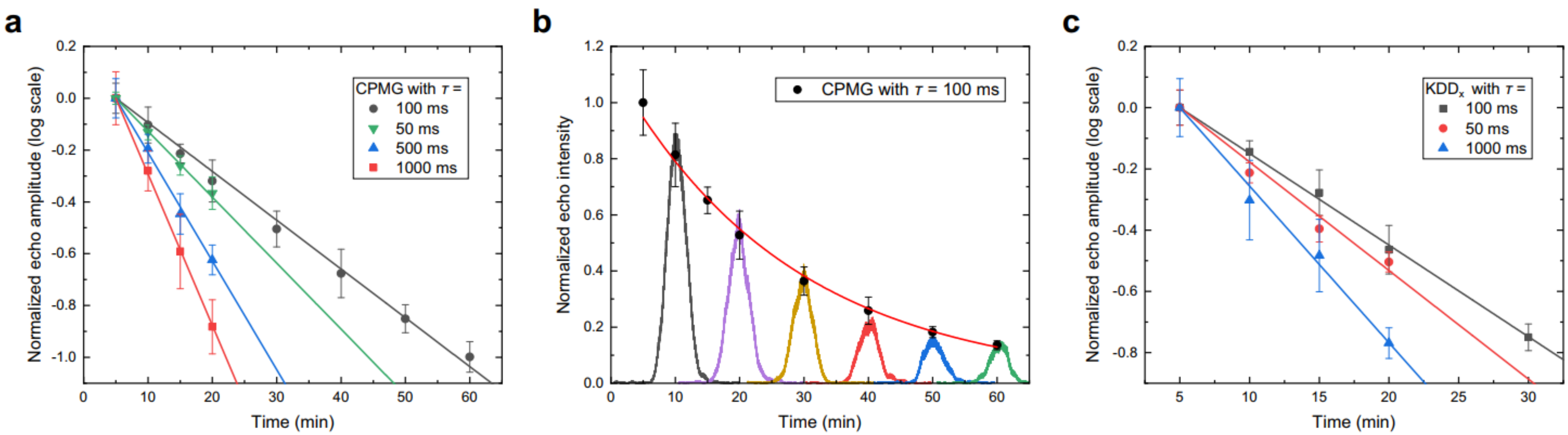




Y. Ma, et al. Nature Commun. 12. 2381 (2021) ESI hot paper

1-hour coherent optical storage

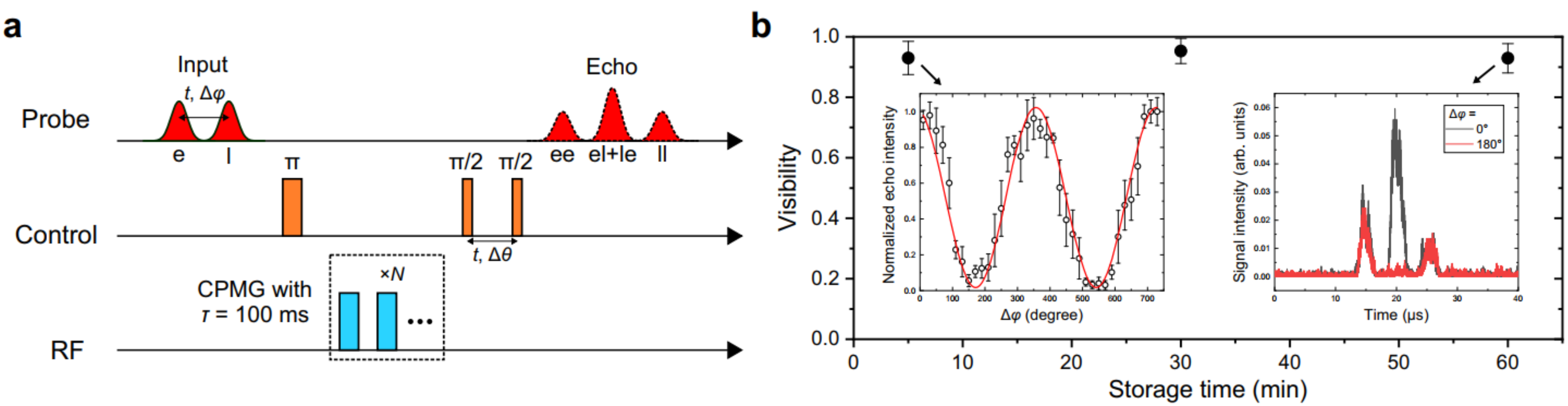
- Optical storage lifetimes up to:
  - CPMG: 52.9±1.2 min
  - KDD_x: 33.3±1.1 min



Y. Ma, et al. Nature Commun. 12. 2381 (2021) ESI hot paper

1-hour coherent optical storage

- Coherent storage for 1 hour
- In principle, considering a speed of 300 km/h, the storage efficiency ($5*10^{-5}$) is already comparable with the transmission of 300-km telecom fiber (10^{-6})
- Significant improvements on the efficiency and the SNR are required for quantum applications



Y. Ma, et al. Nature Commun. 12. 2381 (2021) ESI hot paper

1-hour coherent optical storage

Topical White Paper: A Case for Quantum Memories in Space

Mustafa Gündoğan, Thomas Jennewein, Faezeh Kimiaee Asadi, Elisa Da Ros, Erhan Sağlamyürek, Daniel Oblak, Daniel Rieländer, Jasminder Sidhu, Samuele Grandi, Luca Mazzarella, Julius Wallnöfer, Patrick Ledingham, Lindsay LeBlanc, Margherita Mazzera, Makan Mohageg, Janik Wolters, Alexander Ling, Mete Atatüre, Hugues de Riedmatten, Daniel Oi, Christoph Simon, Markus Krutzik

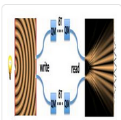
Toptical white paper submitted to National Academies of Sciences, Engineering and Medicine's Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032

- Storage time (τ): in principle a QM should store the input quantum state as long as possible. This is usually limited by interatomic interactions, thermal effects, external magnetic or electric field noises and can be mitigated with several means. Today, QMs are pushing towards 1 s threshold [9], while classical pulse storage for up to 1 h has been recently demonstrated [10].

as a high-performance QM platform. The recent achievements include but are not limited to; heralded entanglement generation between two QMs [69, 70] in a quantum repeater setting, bright pulse storage from minute [71] to hour-long time scales [10] and demonstration of temporal [72–74] spectral [75, 76] and spatial [77] multimode storage.

[10] Y. Ma, Y.-Z. Ma, Z.-Q. Zhou, C.-F. Li, and G.-C. Guo, Nat. Commun. **12**, 2381 (2021).

1-hour coherent optical storage



Quantum memories and the double-slit experiment: implications for astronomical interferometry

Joss Bland-Hawthorn, Matthew J. Sellars, and John G. Bartholomew

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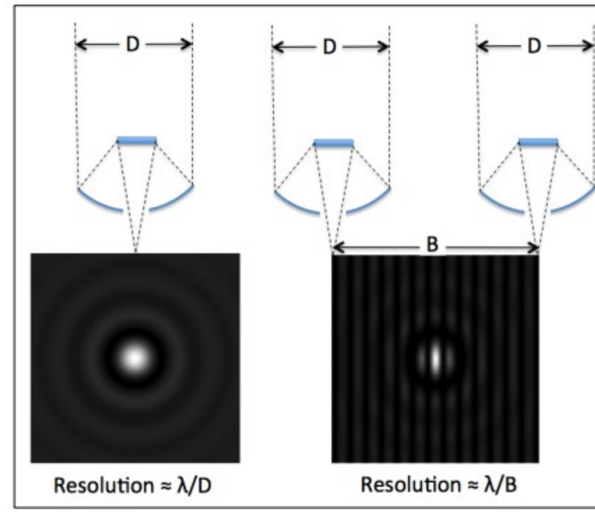
Journal of the Optical Society of America B Vol. 38, Issue 7, pp. A86-A98 (2021) • https://doi.org/10.1364/

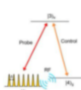
age. Excitingly, the successful mapping and recall of photonic information stored on the optical transition to these long-lived nuclear spin states has recently been demonstrated [28]. In

28. Y. Ma, Y.-Z. Ma, Z.-Q. Zhou, C.-F. Li, and G.-C. Guo, "One-hour coherent optical storage in an atomic frequency comb memory," Nat. Commun. **12**, 2381 (2021).



An unexpected application in astronomy.
Transportable QM can be treated as a novel communication channel.
Its application would not be limited to quantum information science.

1-hour coherent optical storage

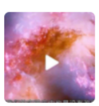


#我国科学家将光存储时间提升至1小时# 热搜

阅读1亿 讨论4719 详情>

主持人：新华网

导语：中国科学技术大学25日发布消息，该校李传锋、周宗权研究组近期成功将光存储时间提升至1小时，大幅刷新8年前德国团队创造的1分钟的世界纪录，向实现量子U盘迈出重要一步。国际学...



#中国科学家把光存储时间提升至1小时# 热搜

阅读6936.2万 讨论6602 详情>

主持人：新华网

导语：光每秒钟可"狂奔"约30万公里，这也是目前人类已知自然界中的最快速度！让人望尘莫及。但近期，中国科学技术大学郭光灿院士团队成功地让光"慢下来"，甚至"停下来"，"封印"在特殊晶...

The Academic Times

Record-smashing photon storage a boon for quantum communicatio

By Zack Fishman

May 11, 2021

Quantum computing just took yet another leap forward. (Unsplash/Ben Wicks)

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NASA's Parker Solar Probe offers first evidence of how the sun flings electrons toward Earth

By Monisha Ravisetti

Solid-state quantum memory

QM based on rare-earth ion doped crystal

PRL 2012

High fidelity

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Wideband and multimode

Nature 2021

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Transportable QM

Long lifetime

Nature Commun. 2021a

High efficiency

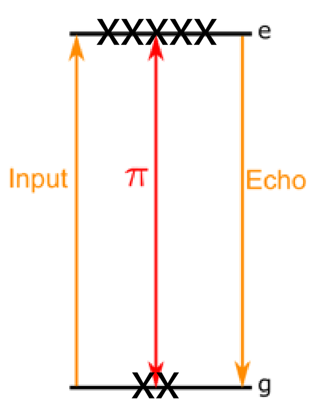
Nature Commun. 2021b
物理学报 2022

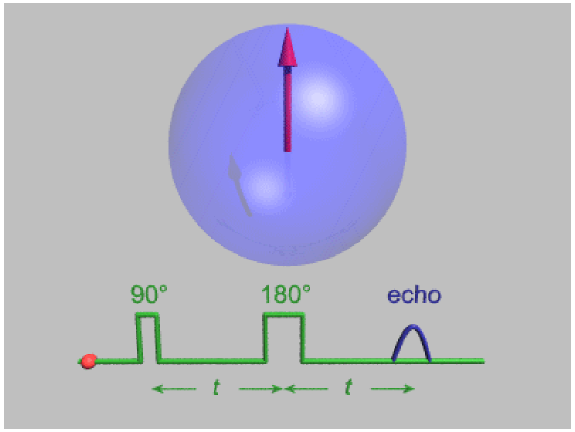
Integrated

Optica 2020
PRL 2020
PRL 2022

Photon echo

- Photon echo in the quantum regime can enable QM with arbitrary frequency bands
- Intrinsic problem: the rephasing pulse brings massive population to the excited state which generates strong spontaneous emission (S.E.) noise





Why the two-pulse photon echo is not a good quantum memory protocol

Jérôme Ruggiero, Jean-Louis Le Gouët, Christoph Simon, and Thierry Chanelière
Phys. Rev. A **79**, 053851 – Published 27 May 2009

Double rephasing

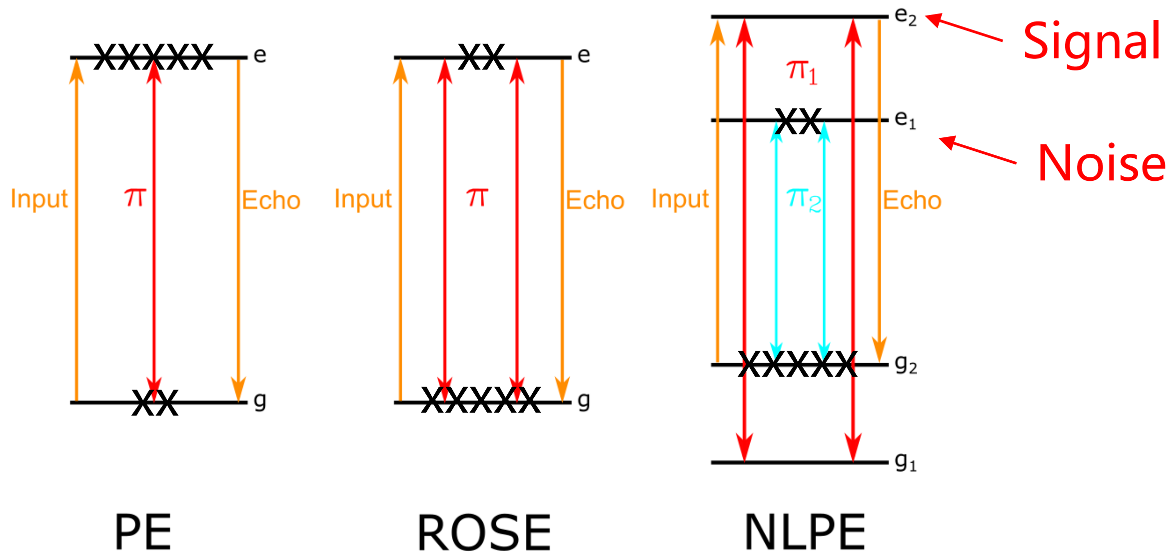
- Double rephasing (e.g. ROSE) is useful, but a slight imperfection in π pulses will leave noisy population in the excited state. The best experimental result so far：a background noise of 1.1 photons.

- A fundamental drawback of previous PE protocols：the excited state which emits signal is the same one which has the noisy population. S.E. noise is indistinguishable.

周宗权，物理学报 71, 070301 (2022)

A Noiseless PE

- NLPE: double rephasing in 4-level atoms
- The excited state that generates the echo and the populated excited state are two different states.
- S.E. noise becomes distinguishable in frequency!



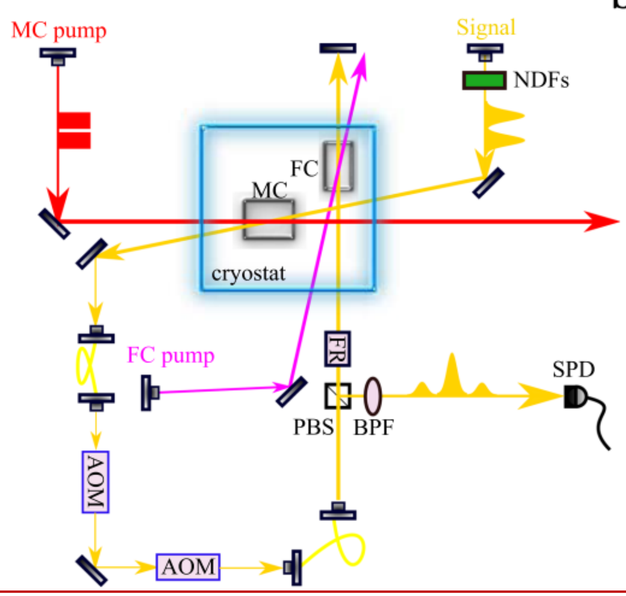
Y.-Z. Ma, et al., Nature Commun. 12. 4378 (2021)

A Noiseless PE

- Measured noise of 0.0015 photons in Eu:YSO
- Storage fidelity for time-bin qubit encoded with weak coherent pulses: 95.2(1.8)%, well above the strict classical bound

Noise before and after the double rephasing is approximately the same.
S.E. noise distinguishable in frequency.

a



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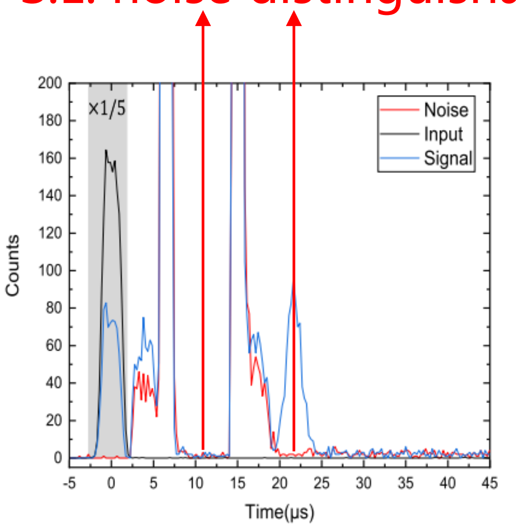

Y.-Z. Ma, et al., Nature Commun. 12. 4378 (2021)

A Noiseless PE

- More efficient than that AFC memory when working with a weakly absorbing sample. Here, η_{NLPE}=10% with d=0.6, while η_{AFC}<2.7%.
- Price: less temporal multimode capacity
- Particularly useful for transportable QM due to the limited sample size to ensure field homogeneity
- May enable the QM for MW photons

Y.-Z. Ma, et al., Nature Commun. 12. 4378 (2021)

A Noiseless PE

Few-photon storage on a second timescale by electromagnetically induced transparency in a doped solid

Marcel Hain[2,1], Markus Stabel[1] and Thomas Halfmann[1]

New Journal of Physics 24, 023012 (2022)

frequency combs (AFC) [11] or controlled reversible inhomogeneous broadening (CRIB) [12, 13]. A recent approach used noiseless photon echos (NLPE) [14]. In contrast to EIT, these protocols do not employ a strong control field which coincides with the signal. However, they also require a time-delayed mapping field to transfer a short-lived optical coherence to a long-lived spin coherence. Nevertheless, as an advantage of AFC, CRIB, and NLPE there is less noise added to the signal by the delayed mapping pulse, which permits a higher storage fidelity. Furthermore, the multimode storage capacity scales more favorably with

[14] Ma Y-Z, Jin M, Chen D-L, Zhou Z-Q, Li C-F and Guo G-C 2021 *Nat. Commun.* **12** 4378

Solid-state quantum memory

QM based on rare-earth ion doped crystal

PRL 2012
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Integrated

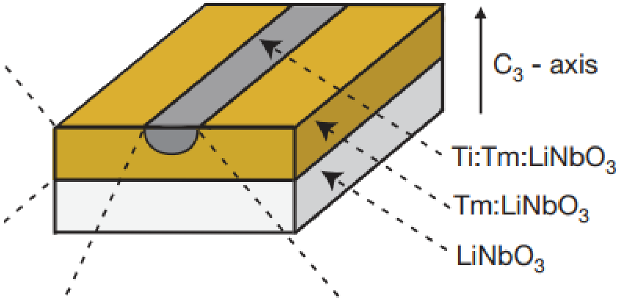
Nature Commun. 2021a

Nature Commun. 2021b
物理学报 2022

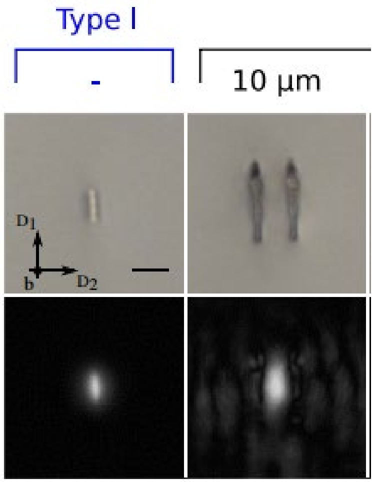
Optica 2020
PRL 2020
PRL 2022

Integrated quantum memories

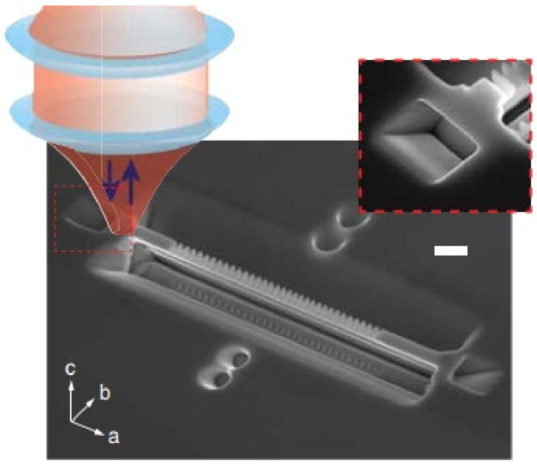
- Standard Ti-indiffused waveguides
- Direct laser written waveguides
- Focused ion beam milled nano-resonanctor



Nature 469, 512 (2011)



Optica 5, 934 (2018)



Science 357, 1392 (2017)

Integrated quantum memories

- Standard Ti-indiffused waveguides
- Direct laser written waveguides
- Focused ion beam milled nano-resonanctor

femtoLAB USTC initial design

Advantages:

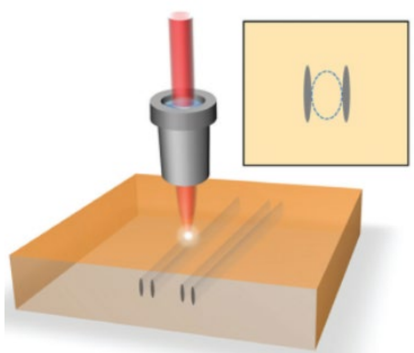
- No impurities
- 3D fabrication
- Well preserved coherent properties

Integrated quantum memories

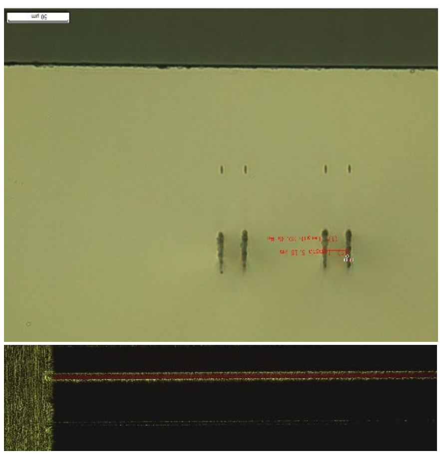
- Challenges：
  - ➢Predetermined storage time， no on-demand retrival
  - ➢No integrated memories demonstrated with the medium for transportable QM (Eu:YSO)

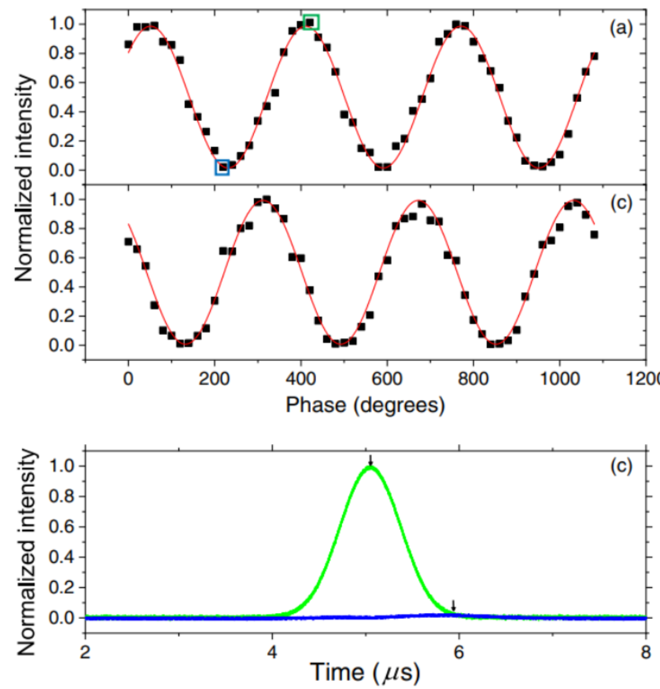
Waveguides in Eu:YSO

- Direct laser written
- Type-II waveguides in Eu:YSO
  - Coherent storage of classical light



Chen et al., LPR 2013

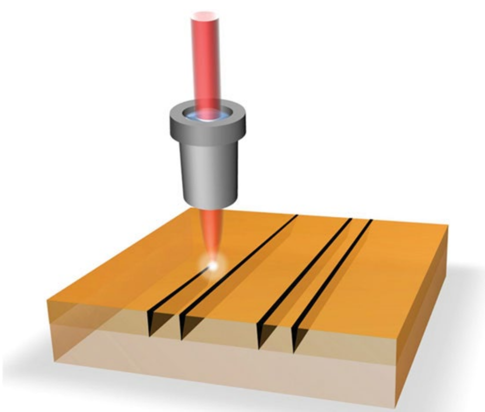




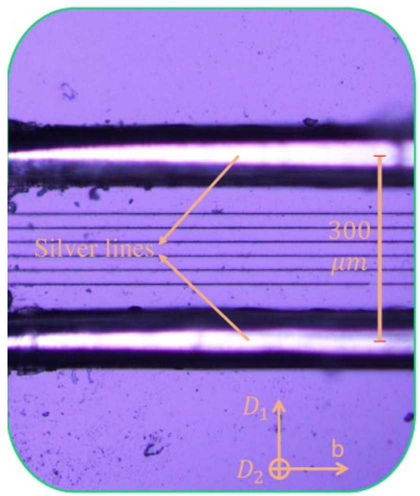
Liu et al., Optica 7, 192 (2020)

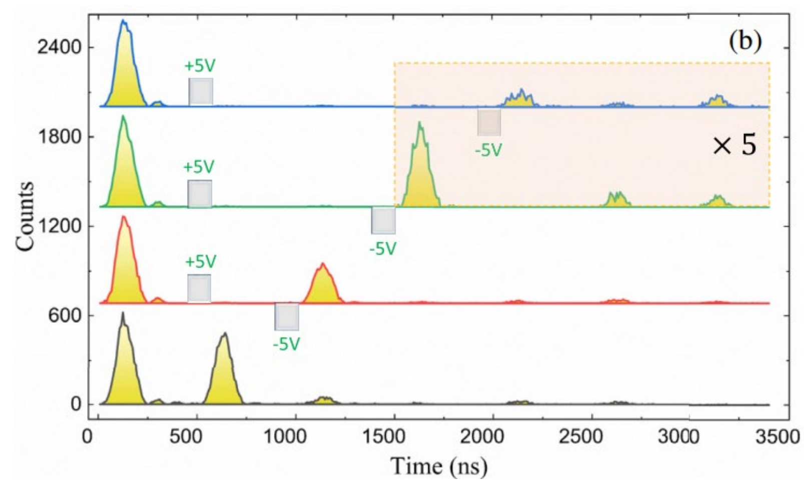
Stark-modulated AFC

- Type-IV on-chip optical waveguides in Eu:YSO
- Combined with on-chip electrodes
  - On-demand storage of time-bin qubits with discrete readout times
  - Low voltages required



Chen et al., LPR 2013

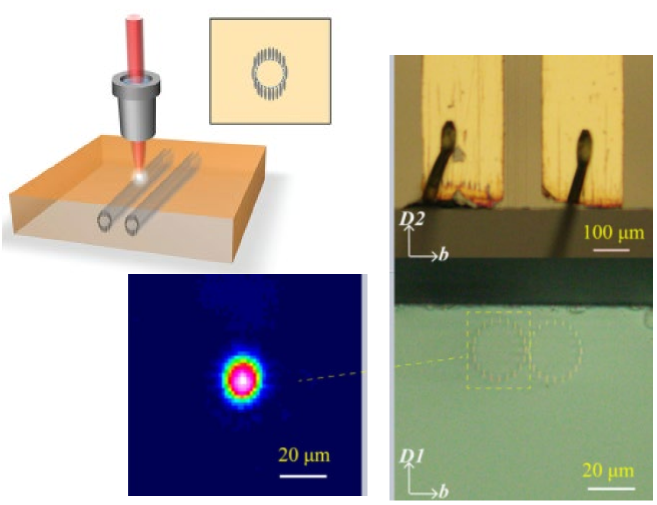


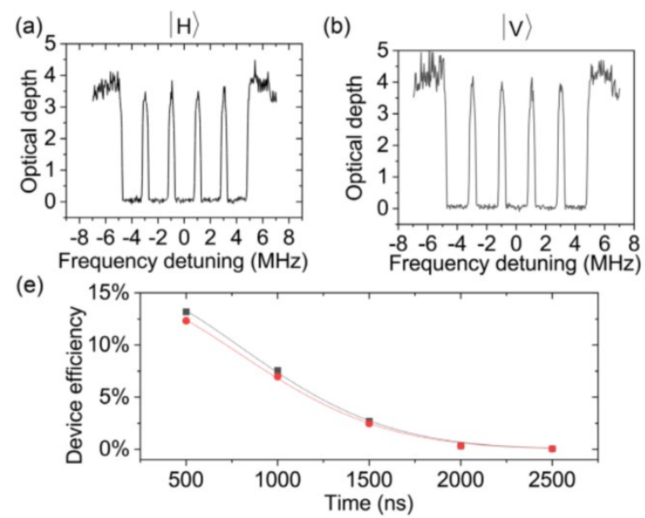


Liu et al., PRL 125, 260504 (2020)

Integrated memories for polarization

- Type-III optical waveguides and with on-chip electrodes
  - Polarization-independent absorption for site-2 Eu in YSO (D1-b)
  - Polarization-independent transmission for the symmetric waveguide
  - A storage fidelity of 99.4(6)%





Zhu et al., PRL 125, 260504 (2022)

Integrated quantum memories

More recently, Zhu et al. [168] have shown that type IV waveguides can be fabricated by FLM in $Er^{3+}:Y_2SiO_5$. A microscope picture of the type IV waveguide and its guided mode profile are reported in Figure 6(d)). Also in this case, it was shown that the coherence properties of the dopant ions inside the waveguide remained unchanged with respect to the bulk crystal. This device was used to demonstrate the coherent storage of classical light pulses at the wavelength of 580 nm adopting the AFC protocol. Since type IV waveguides are fabricated at the crystal surface, this result opens interesting perspectives in coupling laser-written QMs with other surface structures, e.g. coplanar waveguides and/or electrodes, for the coherent driving of the memory operations with external fields, as shown in Ref. [169]. Finally, the same group has demonstrated the inscription of type II waveguides in $Er^{3+}:Y_2SiO_5$ [170], and has used it to implement the storage of classical light pulses employing both the AFC protocol and the Revival Of Silenced Echo protocol (ROSE, see Ref. [171] for details).

DE GRUYTER
Nanophotonics 2021; 10(15): 3789–3812

Review

Giacomo Corrielli, Andrea Crespi and Roberto Osellame*

Femtosecond laser micromachining for integrated quantum photonics

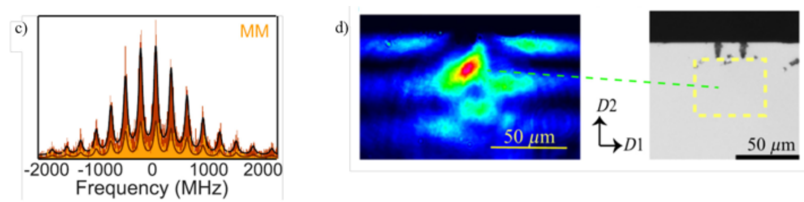


Figure 6: (a) Measurement of the Rabi frequency versus pump power performed in bulk $Pr^{3+}:Y_2SiO_5$ (blue squares) and in a type II waveguide

[168] T.-X. Zhu, C. Liu, L. Zheng, Z.-Q. Zhou, C.-F. Li, and G.-C. Guo, "Coherent optical memory based on a laser-written on-chip waveguide," *Phys. Rev. Appl.*, vol. 14, no. 5, p. 054071, 2020.

[169] Chao Liu, T.-X. Zhu, M.-X. Su, et al., "On-demand quantum storage of photonic qubits in an on-chip waveguide," *Phys. Rev. Lett.*, vol. 125, no. 26, p. 260504, 2020.

[170] C. Liu, Z.-Q. Zhou, T.-X. Zhu, et al., "Reliable coherent optical memory based on a laser-written waveguide," *Optica*, vol. 7, no. 2, pp. 192–197, 2020.

Integrated quantum memories

coupling.[52,225,229] As a result, spin-wave storage with an extended lifetime, which enables long-term storage and on-demand read-out, has been achieved in waveguide-integrated QMs.[50,51,53,230] A great amount of effort has been devoted to this topic, mainly focused on the geometry of type I, type II, and ridge waveguides.

shown in Figs. 15(a)–15(d). Later in 2020, using the type II waveguides in $Eu^{3+}:Y_2SiO_5$ crystals, on-demand light storage was demonstrated via the spin-wave atomic frequency comb (AFC) and the storage fidelity was quantitatively characterized for the first time.[50] Compared to type II waveguides, the fabri-

scheme.

Considering that the channel waveguides (type I and type II) are fabricated at a depth beneath the crystal surface, ridge waveguide-based QMs are easily integrated with other on-chip devices, allowing for constructing large-scale quantum networks. In 2020, a laser-written ridge waveguide was successfully fabricated in an $Eu^{3+}:Y_2SiO_5$ crystal, in which the properties of the Eu^{3+} ions were well-preserved.[230] The spin-wave AFC storage was implemented, confirming high-interference visibility [Figs. 16(a)–16(d)]. In 2021, their group achieved a better fabrication parameter, realizing 40% end-to-end device efficiency, while the typical coupling efficiency is 10% in $LiNbO_3$ waveguide memory. Combined with on-chip electrodes, a high storage fidelity of $99.3\% \pm 0.2\%$ and on-demand storage of time-bin qubits were demonstrated,[51] far beyond that value of the classical measure-and-prepare strategy.

ADVANCED PHOTONICS

Femtosecond laser-inscribed optical waveguides in dielectric crystals: a concise review and recent advances

Lingqi Li,[a] Weijin Kong,[a] and Feng Chen[b,*]

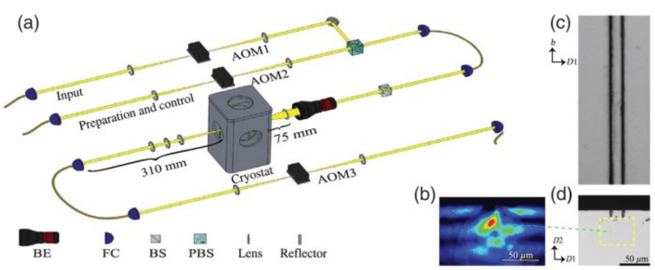


Fig. 16 (a) Experimental setup of coherent optical memory based on an on-chip waveguide.

50. C. Liu et al., "Reliable coherent optical memory based on a laser-written waveguide," *Optica* **7**(2), 192–197 (2020).
51. C. Liu et al., "On-demand quantum storage of photonic qubits in an on-chip waveguide," *Phys. Rev. Lett.* **125**(26), 260504 (2020).
230. T.-X. Zhu et al., "Coherent optical memory based on a laser-written on-chip waveguide," *Phys. Rev. Appl.* **14**(5), 054071 (2020).

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- Introduction
- Solid-state quantum memory
- **Summary**

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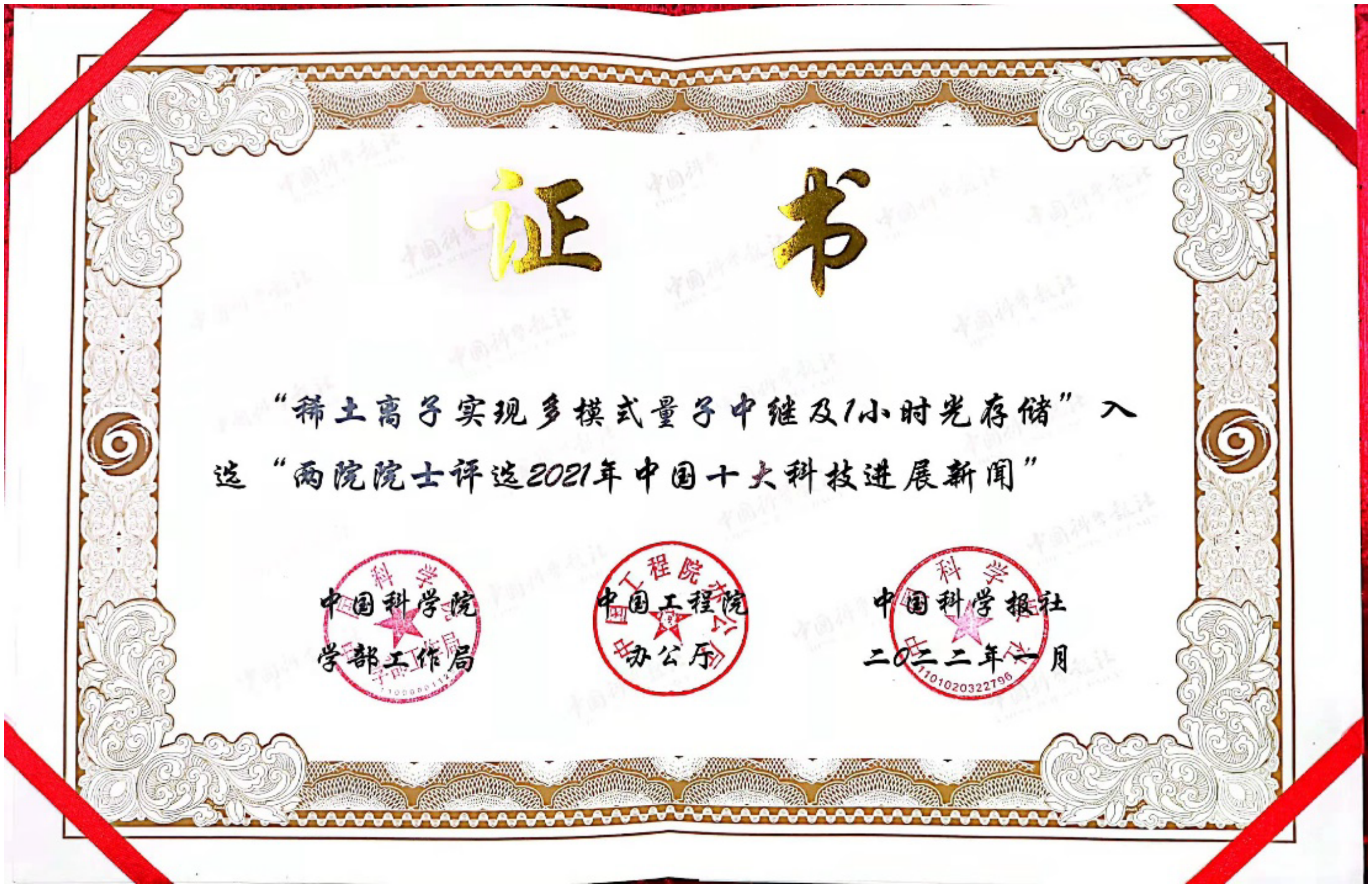

Top 10 S&T achievements in Universities

教 育 部 司 局 函 件

教技委〔2022〕2 号

**教育部科学技术委员会关于公布 2021 年度
“中国高等学校十大科技进展”
入选项目的通知**

中国科学技术大学:

2021 年度“中国高等学校十大科技进展”评审工作已经结束。你校李传锋完成的“基于稀土离子的固态量子存储”入选 2021 年度“中国高等学校十大科技进展”。

特此通知。

教育部科学技术委员会

2022 年 4 月 14 日

Summary

- **Multiplexed quantum repeater**

➢ based on absorptive QM

X. Liu#, Hu#, Li, Li, Li, Liang, **Zhou***, Li*, Guo, Nature 594, 41 (2021)

- **Transportable QM**

➢ Coherent light storage for 1 hour

Y. Ma, Ma, **Zhou***, Li*, Guo, Nature Commun. 12, 2381 (2021)

➢ NLPE protocol for higher efficiencies

Y.-Z. Ma#, Jin#, Chen#, **Zhou***, Li*, Guo, Nature Commun. 12, 4378 (2021)

➢ Integragted QM

Optica 2020, PRL 2020, PRL 2022

Summary

- **Multiplexed quantum repeater**

➢ A field-test with telecom interface

- **Transportable QM**

➢ Quantum storage for 1 hour