集成光子芯片微腔与单原子耦合

从传统腔QED到片上量子光学

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讲座内容概览

Part 1: 集成光量子芯片

Part 3: 片上单原子强耦合

Part 2: 腔量子电动力学基础

Part 4: 我们的实验进展

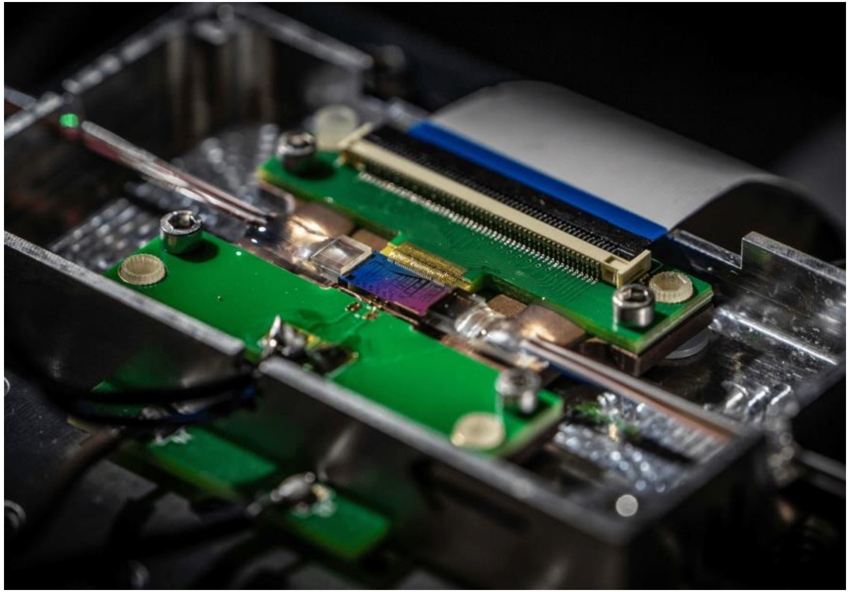
Part 5: 总结与展望

Part 1

集成光量子芯片

Quantum Photonic Integrated Chip

光量子信息



很难相互作用

偏振，路径，OAM，
波导模式等

免疫噪声

编码方式多样

光子

易于实现单比特操作

分束器，相位器，
波片等

高速传输

与其他体系结合

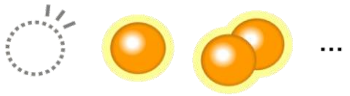
299792458m/s，通信

单光子的场效应管？

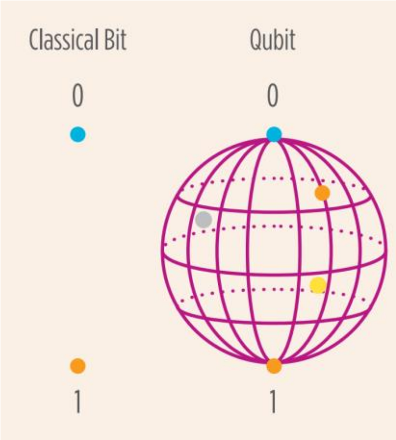
光量子比特 qubit

Qubit

0 1 2 ···

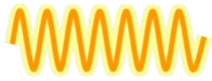


Particle nature of light



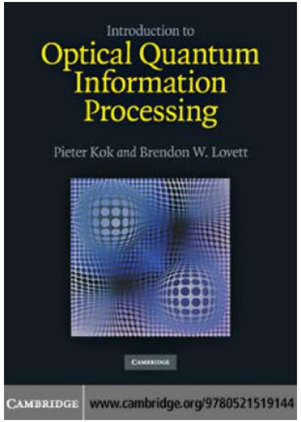
Continuous variable

Amplitude & phase



Wave nature of light

Kok, P., & Lovett, B. W. (2010). *Introduction to optical quantum information processing*.



光量子比特 qubit

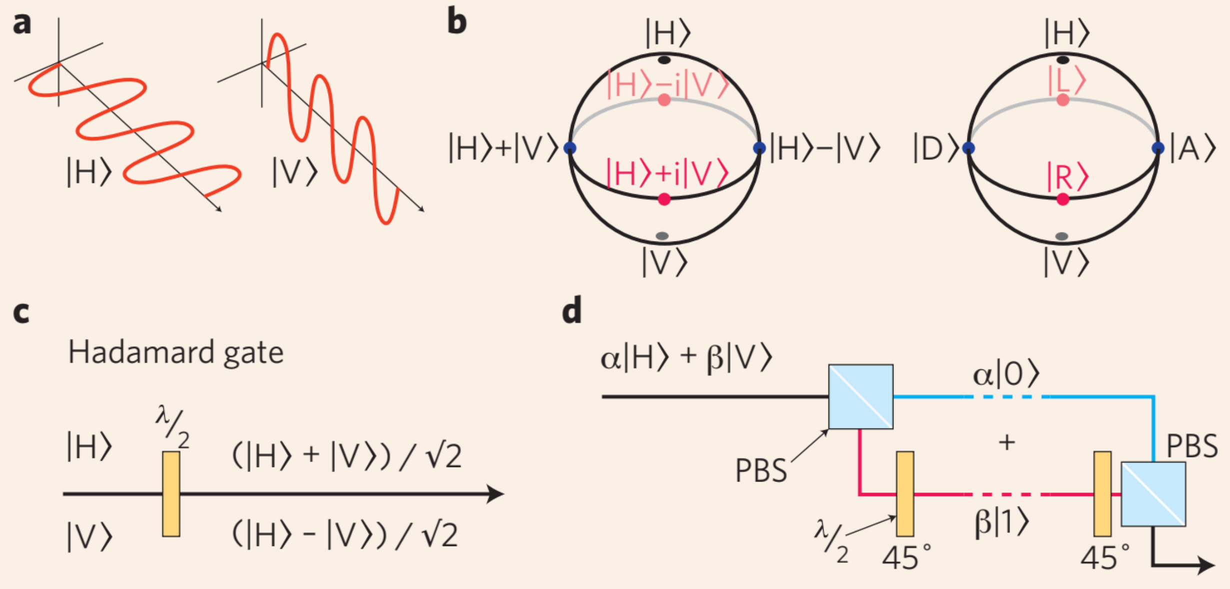
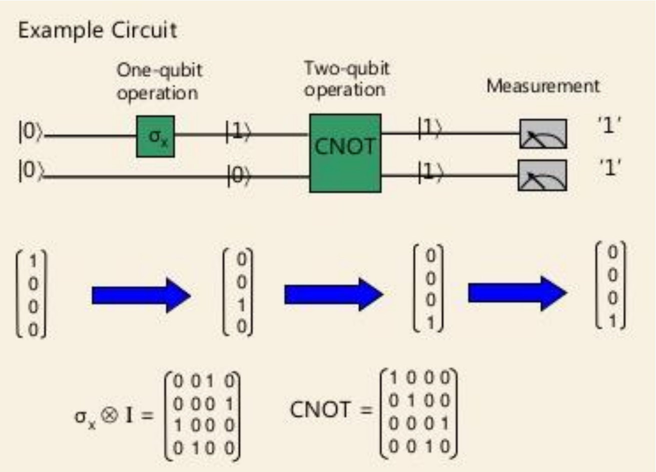


Figure 1 | Encoding and manipulating a qubit in a single photon.

O’Brien, J. L., Furusawa, A., & Vučković, J. (2009).
Photonic quantum technologies. *Nature Photonics*, *3*(12), 687–695.

光量子信息处理



量子初态制备－量子操作－量子测量

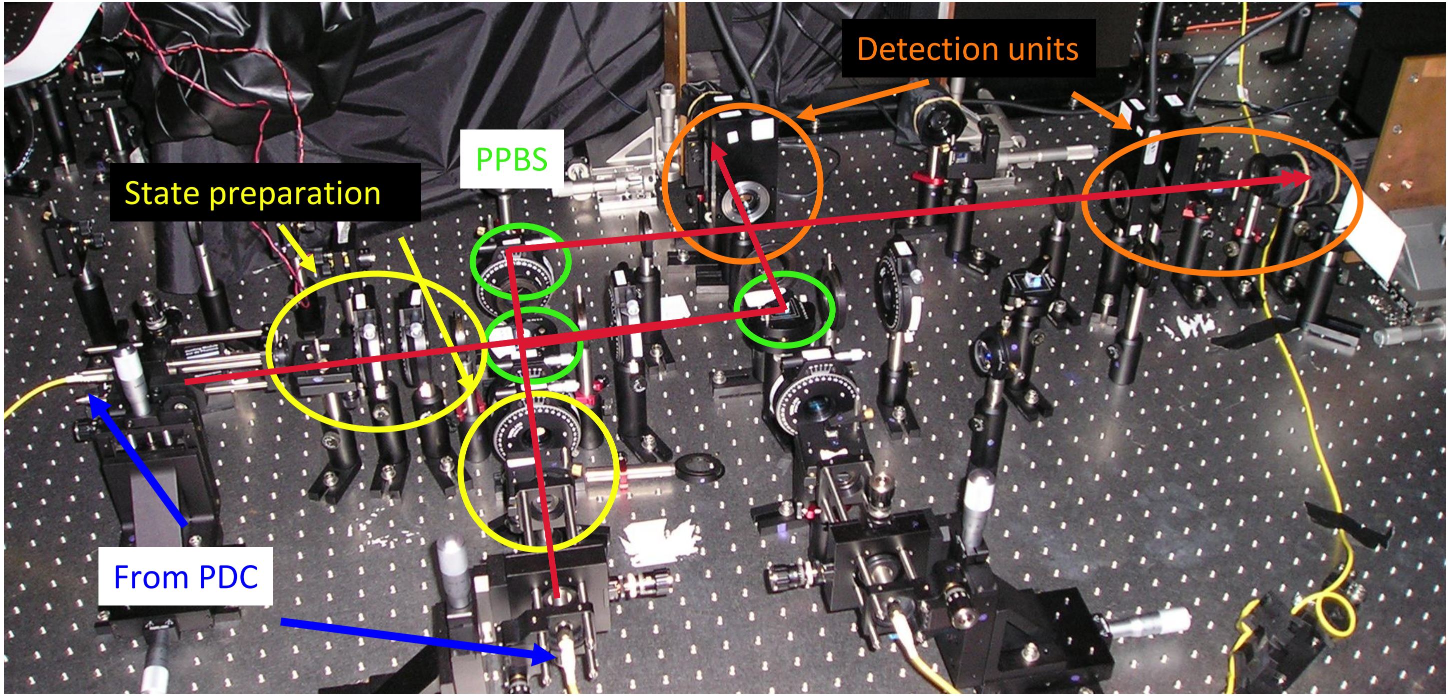
光源－调制－探测

不可克隆！

光强放大、经典信息拷贝

光源：单光子；高保真度、低损耗的量子器件；两比特量子门：单光子级非线性相互作用；高效率单光子探测器

传统光量子信息处理

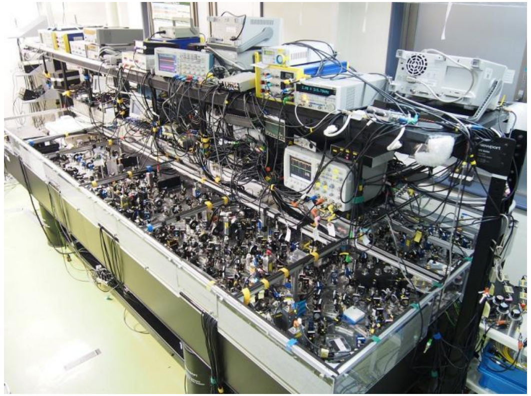


1 m

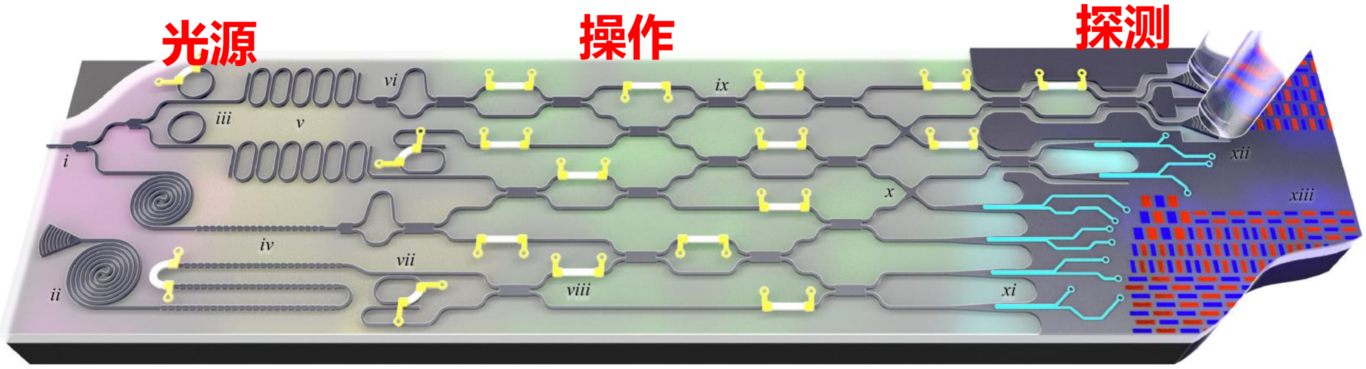
Controlled-NOT Gate

N. K. Lanford *et al., Phys. Rev. Lett.* **95,** 210504 (2005)

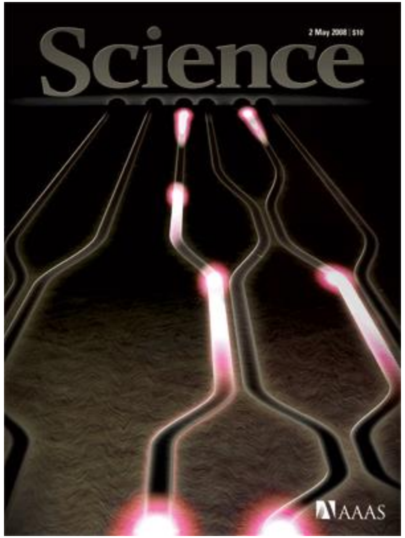
集成光量子芯片



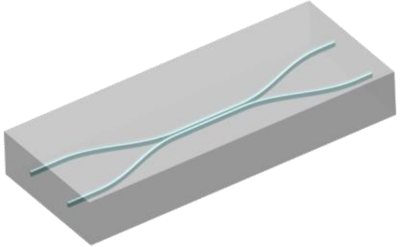
优点:
- ❖ 尺寸小
- ❖ 稳定
- ❖ 可扩展
- ❖ 低功耗

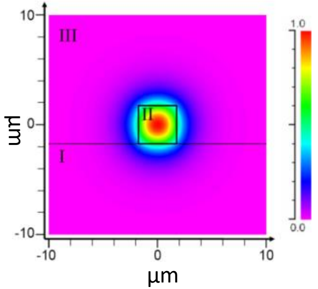


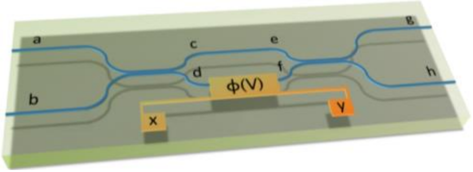
集成光量子芯片发展

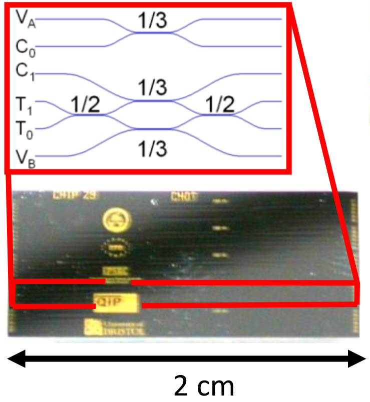


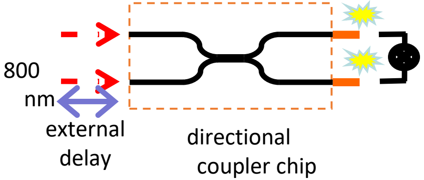
- ***Silica-on-silicon waveguide***







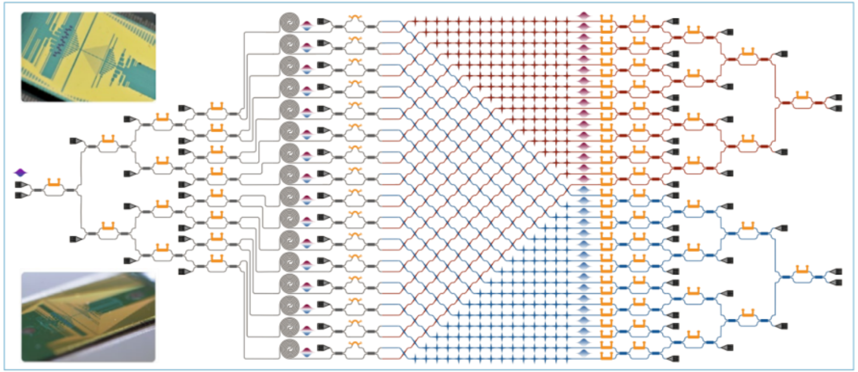


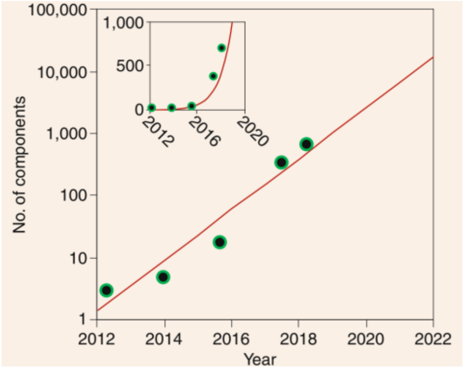


J. L. O'Brien group

1. *Science, 320, 5876 (2008),*
2. *Nature Photonics, 3, 346 (2009).*
3. *Optics. Exp. 17, 12546 (2009),*
4. *Science 325，1221，（2009），*
5. *IEEE 15, 1673 (2009)*

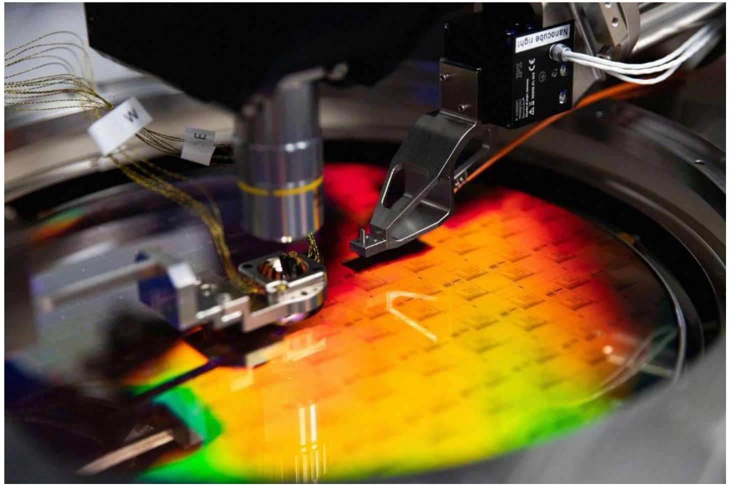
集成光量子芯片发展





A state-of-the-art large-scale integrated quantum photonic circuit in silicon. The device fully integrates **16 waveguide SPSs (spirals), 93 reconfigurable TOPSs (orange parts), 122 MMIs, 376 crossers and 64 grating couplers, in total 671 optical components**. The device was re-programmed to demonstrate the on-chip GMM of multidimensional entangled states with high controllability and universality, to certificate up to 15×15 dimensional two-photon entangled states, and to implement multiple quantum information tasks. The two insets are photographs of the device. Silicon waveguides and 16 SFWM sources can be observed as blue lines. Gold wires allow the electronic access of each TOPS.

集成光量子芯片发展



PsiQuantum CEO Jeremy O'Brien

近日，硅谷初创公司PsiQuantum Corp.已经从投资者那里**筹集了2.15亿美元**，其投资方包括微软公司的M12风险投资部门、贝莱德顾问公司（BlackRock Advisors），Founders Fund，Atomico和Redpoint Ventures。PsiQuantum正在努力开发一种基于光子技术的100万物理量子比特量子计算机，该计算机具有广泛的纠错功能，可以在半导体晶圆厂中制造。

集成光量子芯片：挑战

- ➢缺乏优质的量子光源 （概率性，不可扩展）

传统上利用参量光下转换方法产生的纠缠光子对，在产生时间和光子状态上带有不确定性，这严重制约了量子通讯的可靠性以及量子计算的保真度。

- ➢量子门操作（概率性、不可扩展）

由于光子间的相互作用较弱，实验上通常需要使用各种干涉仪来完成概率性的量子门操作。对于复杂的多光子系统，干涉仪数目的大量增加，会导致系统稳定性及其能耗、操作成功概率等一系列严重的问题。

解决方案：利用单光子量级非线性相互作用实现量子光源和量子门

Part 2

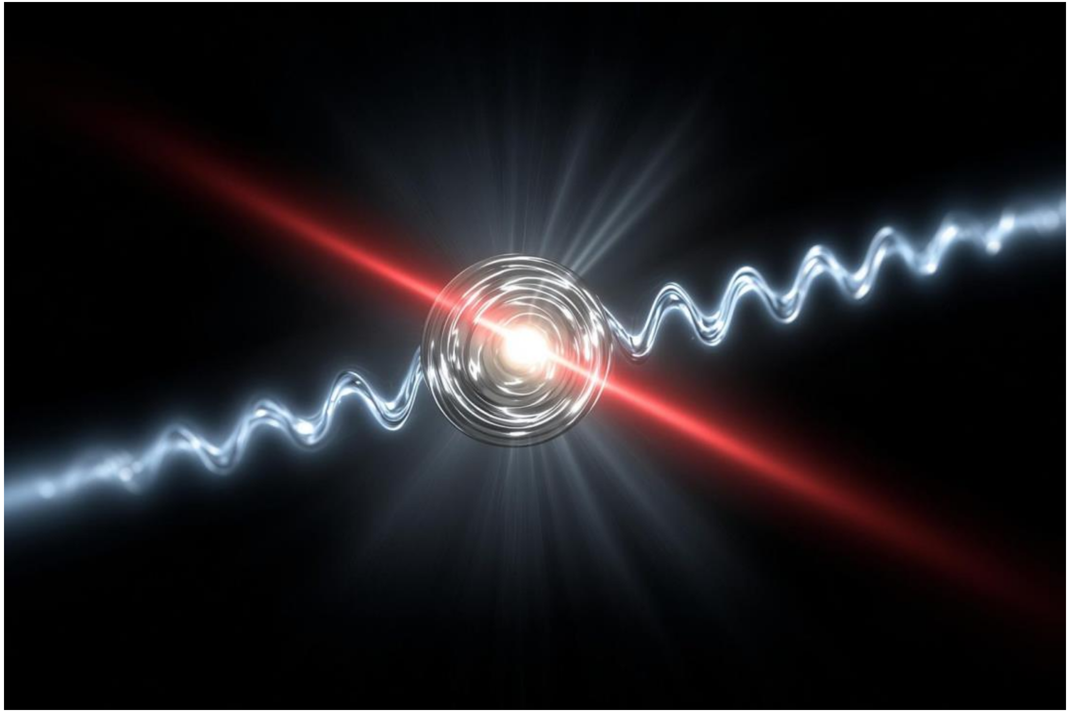
腔量子电动力学基础

Cavity Quantum Electrodynamics Fundamentals

芯片为什么需要原子?

芯片上光量子信息处理缺乏实现光子量子门的手段!

介质中直接的光子-光子相互作用太弱



什么是腔量子电动力学 (Cavity QED)?

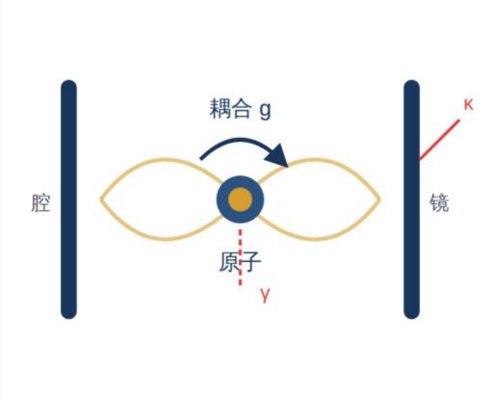
腔QED 研究的是**单个量子发射体**（如原子）与**高品质因子光学腔**中量子化电磁场模式之间的相互作用。

核心要素:

腔　原子

关键物理量:

g — 原子-光子耦合强度
κ — 腔场衰减率
γ — 原子自发辐射率



腔QED基本示意图

Jaynes-Cummings 模型 (1963)

系统哈密顿量：

$$\hat{H} = \hbar\omega_c\hat{a}^\dagger\hat{a} + \frac{1}{2}\hbar\omega_a\hat{\sigma}_z + \hbar g(\hat{\sigma}^+\hat{a} + \hat{\sigma}^-\hat{a}^\dagger)$$

第一项：腔场能量（光子数 × 光子能量）

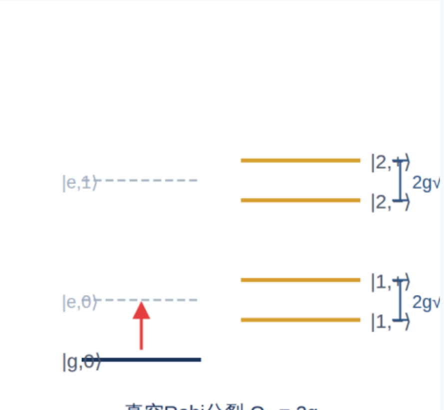
第二项：原子能量（二能级系统）

第三项：原子-光子相互作用（旋波近似）

> **核心物理**：描述单个二能级原子与单模量子化光场的相干相互作用，是腔QED的理论基石。

历史：1963年由E.T. Jaynes和F.W. Cummings提出，1987年首次在实验中得到验证。

缀饰态能级图



真空Rabi分裂 $\Omega_0 = 2g$

强耦合条件与协作参数

强耦合条件

$$g \gg \kappa, \gamma$$

耦合强度远大于损耗率

协作参数

$$C = g^2 / (\kappa\gamma) \gg 1$$

衡量相干性的关键指标

耦合强度 g

$g \propto d \cdot \sqrt{(\omega/V)}$
d: 偶极矩，V
: 有效模式体积
→ 减小腔模体积可增强g

腔损耗率 κ

$\kappa = \omega / Q$
Q: 品质因子

→ 高Q值腔可降低κ

原子衰减率 γ

$\gamma \propto d^2 \omega^3$
自发辐射到其他模式

→ 选择合适的原子跃迁

强耦合的物理意义:

✓ 原子与光子可以多次相干交换能量（Rabi振荡）　✓ 系统呈现明显的量子特性（真空Rabi分裂）　✓ 可实现确定性的量子态操控

真空Rabi分裂：强耦合的标志

当原子与腔共振时，即使腔内没有光子，原子-腔系统的能级也会发生**分裂**，称为**真空Rabi分裂**。

物理解释：

原子激发态 |e,0⟩ 与腔激发态 |g,1⟩ **简并**

耦合导致形成新的**缀饰态**（dressed states）

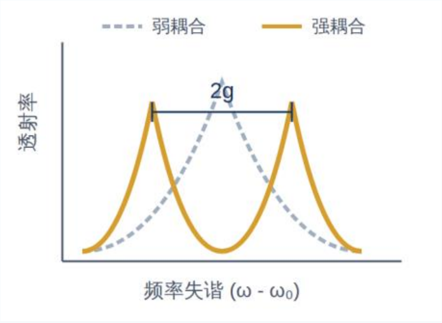
分裂大小 = 2g（真空Rabi频率）

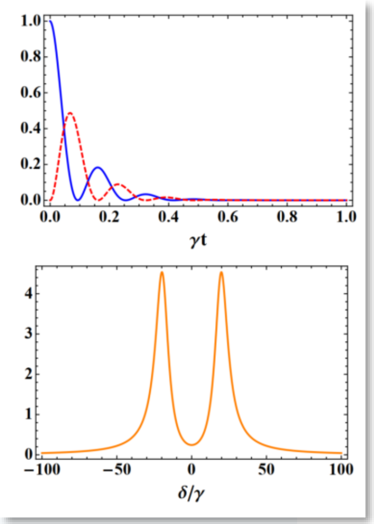
缀饰态波函数：

$$|\pm\rangle = (|e,0\rangle \pm |g,1\rangle) / \sqrt{2}$$

实验观测：通过透射谱或反射谱测量，可观察到单峰分裂为双峰，分裂间距即为2g。

透射谱示意图





真空Rabi分裂是**判断强耦合**的重要实验证据

腔QED发展里程碑

JC模型提出
Jaynes & Cummings

Rabi振荡观测
微波腔+里德堡原子

JC模型验证
Rempe, Walther, Klein

光学腔强耦合
Kimble组

单原子探测
确定性俘获

微波腔QED

使用超导微波腔（Q~10^{10}）与里德堡原子，实现了最早的强耦合实验。代表人物：Haroche, Walther。

光学腔QED

使用Fabry-Pérot光学腔与冷原子，工作在可见光/近红外波段。代表人物：Kimble, Rempe。

诺贝尔物理学奖 2012

S. Haroche 和 D. Wineland 因"开创性的实验方法使单个量子系统的测量和操控成为可能"获奖。

传统腔QED

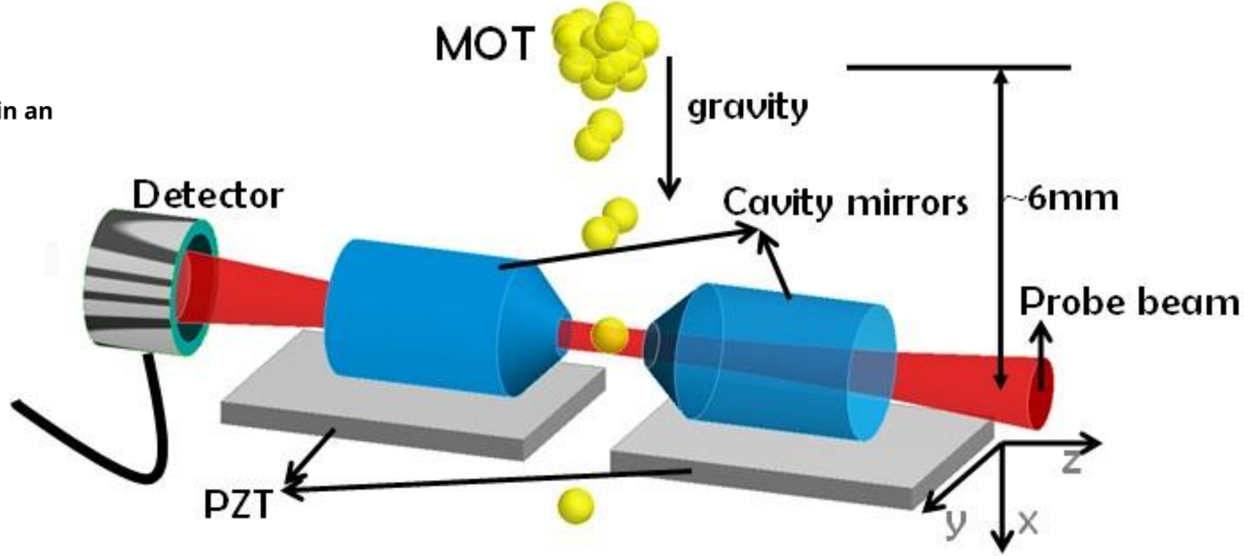
Observation of normal-mode splitting for an atom in an optical cavity

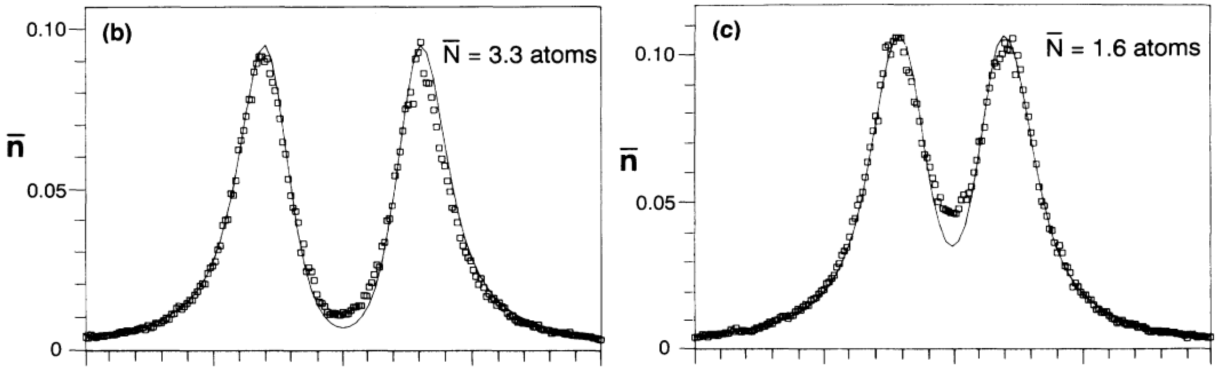
R. J. Thompson, G. Rempe, and H. J. Kimble

Show more

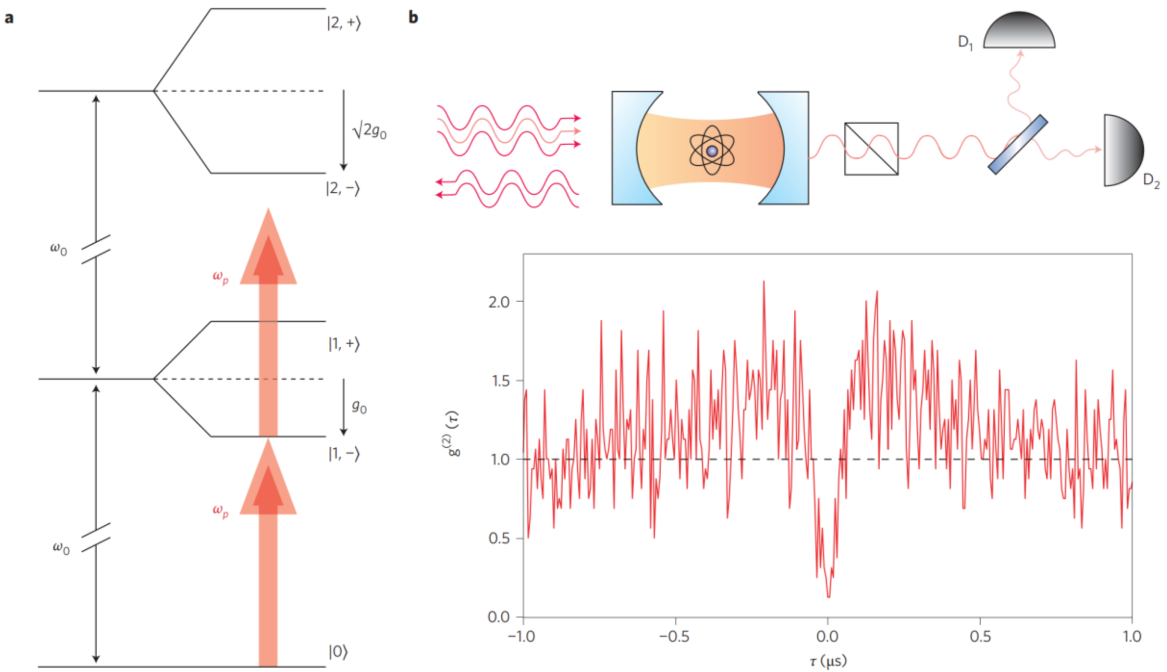
Phys. Rev. Lett. **68**, 1132 – **Published 24 February, 1992**

DOI: https://doi.org/10.1103/PhysRevLett.68.1132



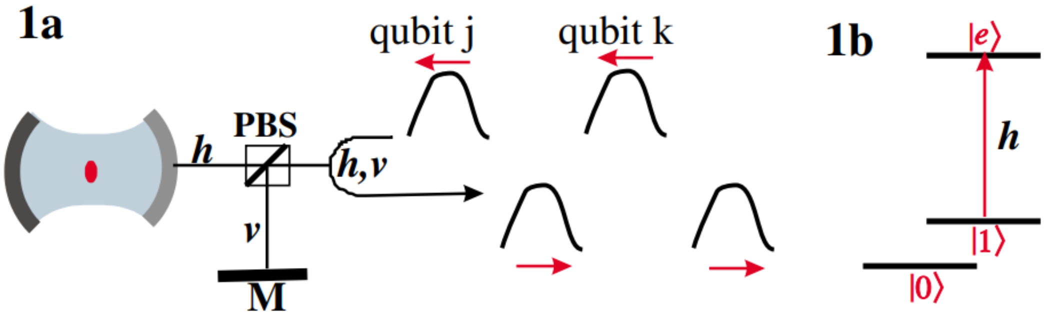


单光子阻塞

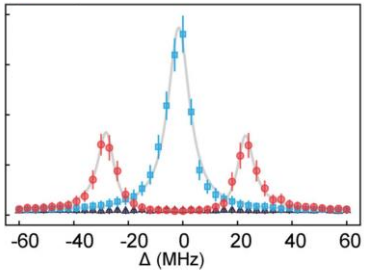


K. M. Birnbaum, A. Boca, R. Miller, A. D. Boozer, T. E. Northup, and H. J. Kimble,
"Photon blockade in an optical cavity with one trapped atom.," Nature **436**, 87 (2005).

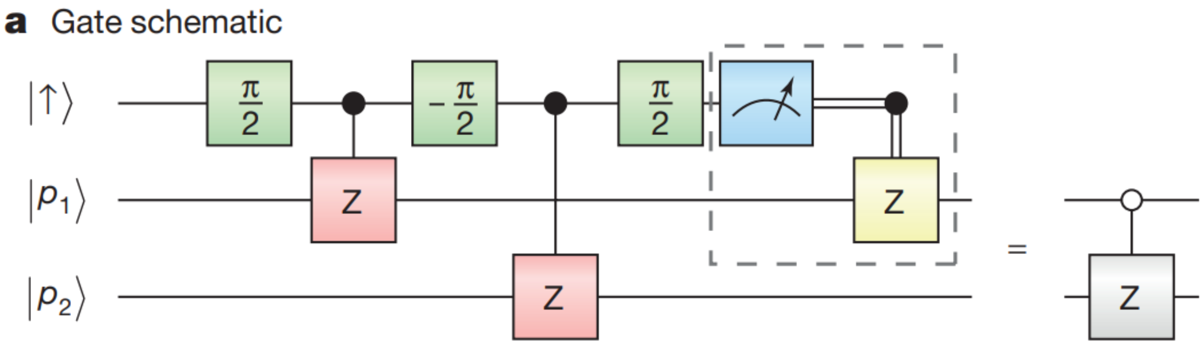
Duan-Kimble scheme



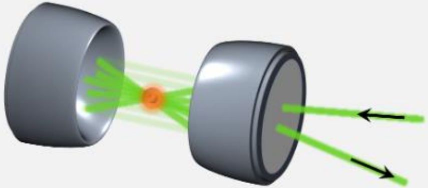
Atom-photon gate
Duan, Kimble 2004



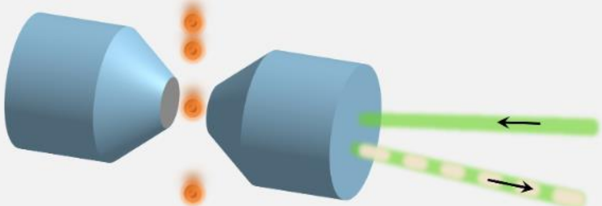
A photon–photon quantum gate based on a single atom in an optical resonator
Rempe (2016)



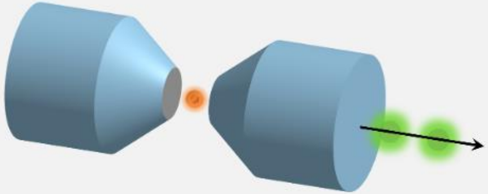
1946 Purcell effect



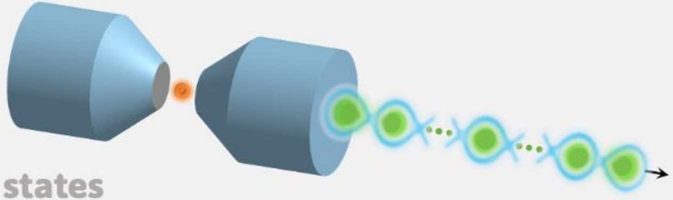
1995 Conditional phase



1999 Atom trapping & cooling
2004 Single-photon generation



2014 CZ quantum gate
2016 Atom-photon GHZ
2022 Multi-photon graph states



Part 3

集成光子芯片上的单原子强耦合

On-Chip Atom-Photon Strong Coupling

传统腔QED系统的局限性

体积庞大

传统F-P腔需要高精度光学元件，整个实验系统占据整个光学平台，难以小型化。

对准困难

腔镜对准精度要求极高（亚微米级），机械振动敏感，需要复杂的稳定系统。

环境苛刻

微波腔需要毫开尔文低温环境，光学系统需要超高真空，运行成本高昂。

难以扩展

每个腔-原子系统相互独立，难以实现多节点互连，无法构建量子网络。

成本高昂

高品质因子腔镜制造成本高，每套系统需要独立调试，难以批量生产。

集成受限

难以与其他光学/电子元件集成，无法实现片上全光子量子信息处理。

核心需求：发展紧凑、可扩展、易于集成的新型原子-光子接口平台，推动量子技术从实验室走向实用化

集成光子芯片的独特优势

超小模式体积

Veff ~ (λ/n)³，比传统腔小10³-10⁶倍

增强的耦合强度

g ∝ 1/√Veff，可达数百 MHz

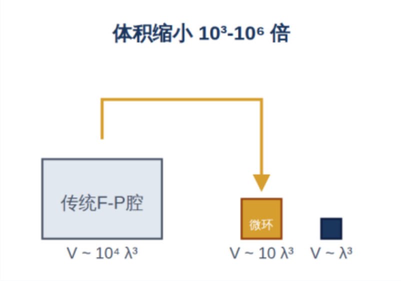
天然集成能力

可与波导、分束器、调制器等集成

可扩展性强

CMOS兼容工艺，可批量制造

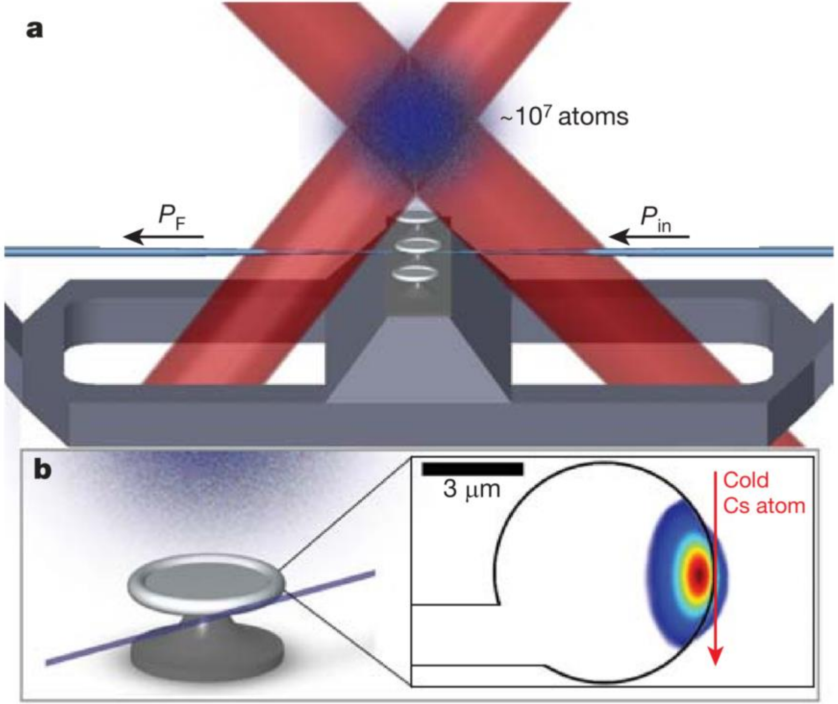
模式体积对比

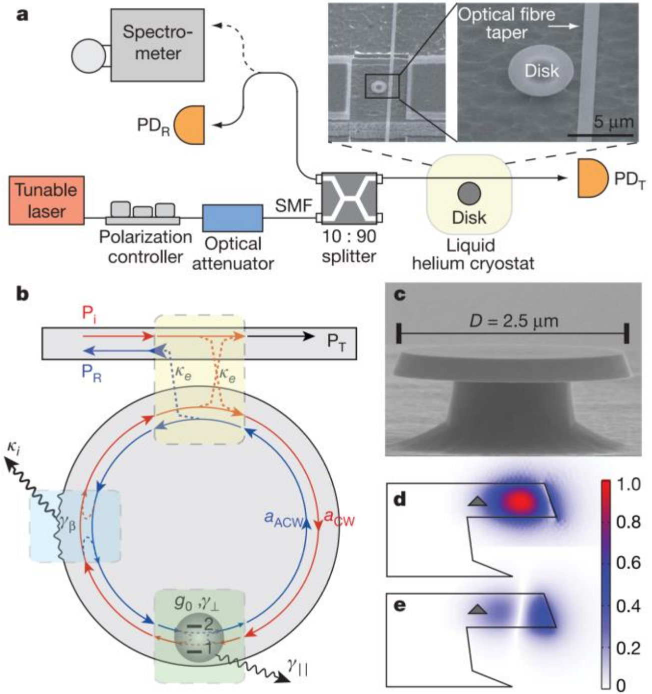


关键公式：

$g = d\cdot\sqrt{(\omega/2\varepsilon_0\hbar V)}$

非确定性的芯片CQED





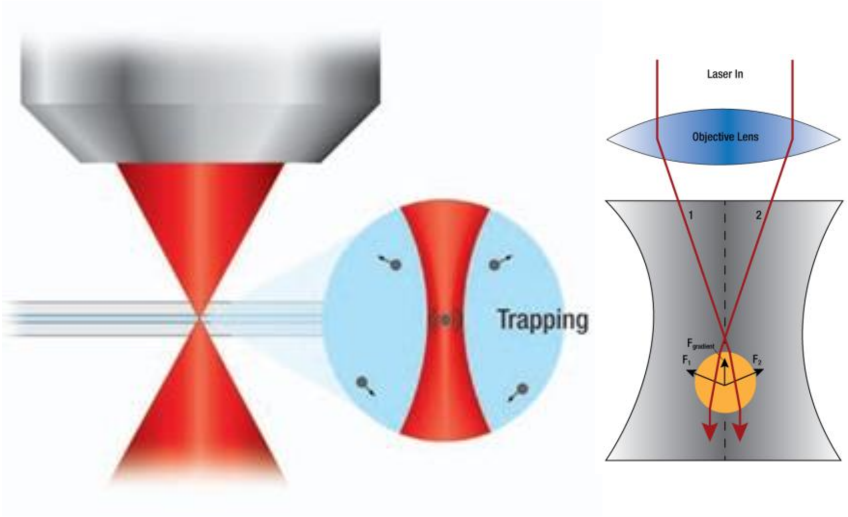
原子概率性下落，相互作用时间短

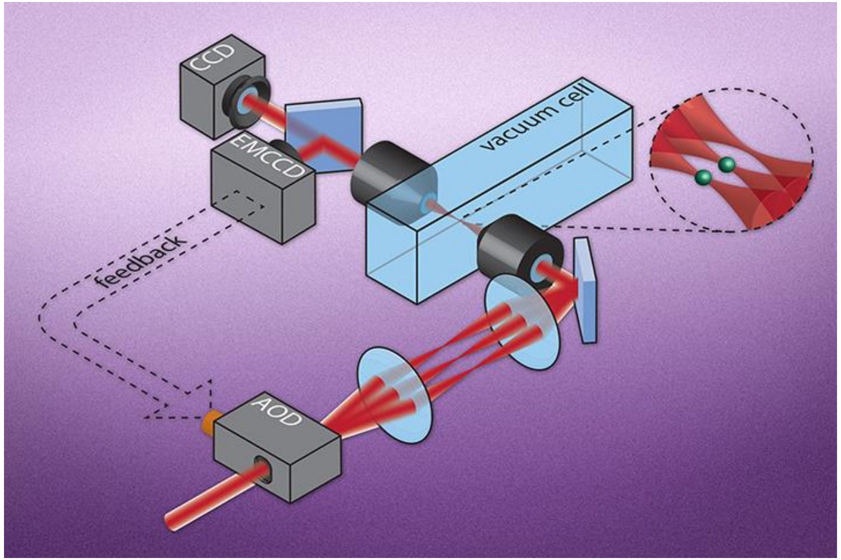
人工原子概率性生长，无全同性

K. J. Vahala, and H. J. Kimble, Nature **443**, 671 (2006).

K. Srinivasan and O. Painter, Nature **450**, 862 (2007).

原子光镊技术





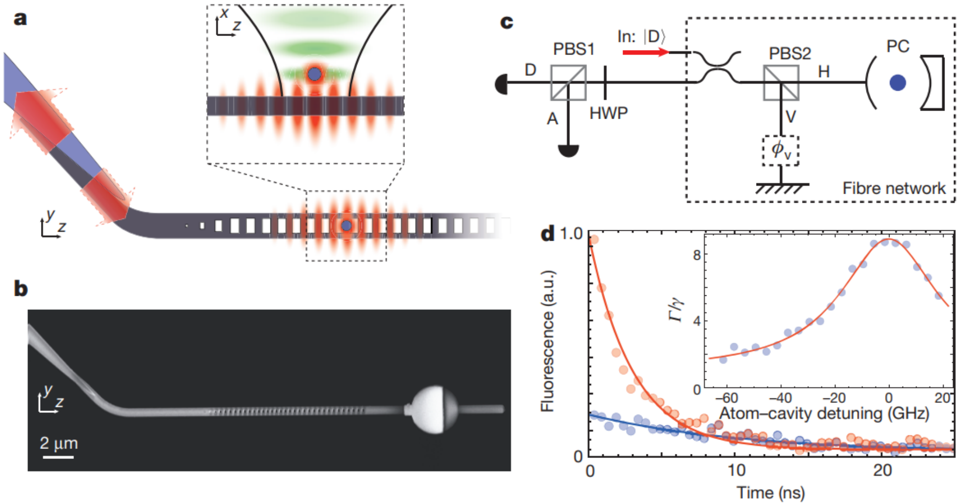
散射力：激光冷却
梯度力：光镊 >>> 原子囚禁

M. D. Lukin, Science **354**, 1024(2016)

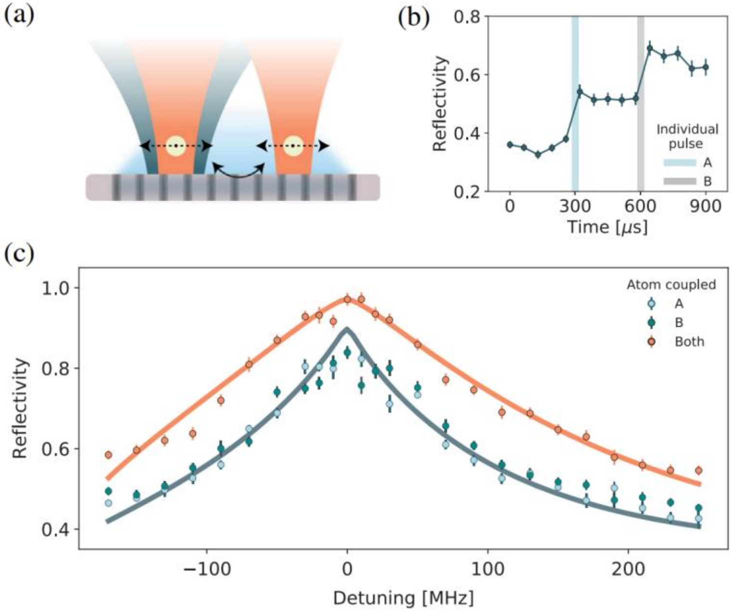
悬空光子晶体微腔

2014年进展：Harvard大学团队实现了单原子在微腔上的囚禁和强耦合

2020年：2个原子



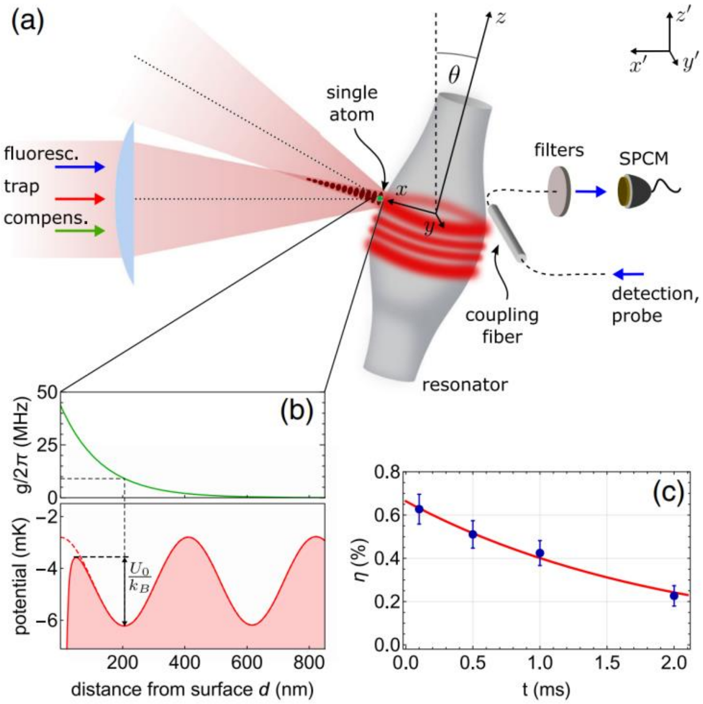
T. G. Tiecke, J. D. Thompson, N. P. de Leon, L. R. Liu, V. Vuletić, and M. D. Lukin, "Nanophotonic quantum phase switch with a single atom," Nature **508**, 241–244 (2014).

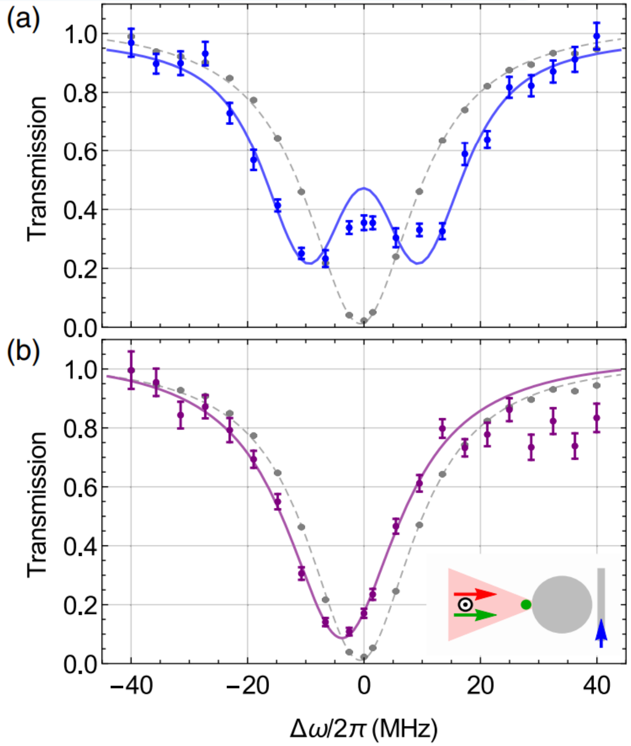


P. Samutpraphoot, T. Đorđević, P. L. Ocola, H. Bernien, C. Senko, V. Vuletić, and M. D. Lukin, "Strong Coupling of Two Individually Controlled Atoms via a Nanophotonic Cavity," Phys. Rev. Lett. **124**, 063602 (2020).

光纤微腔

概率性的抓取下落的原子

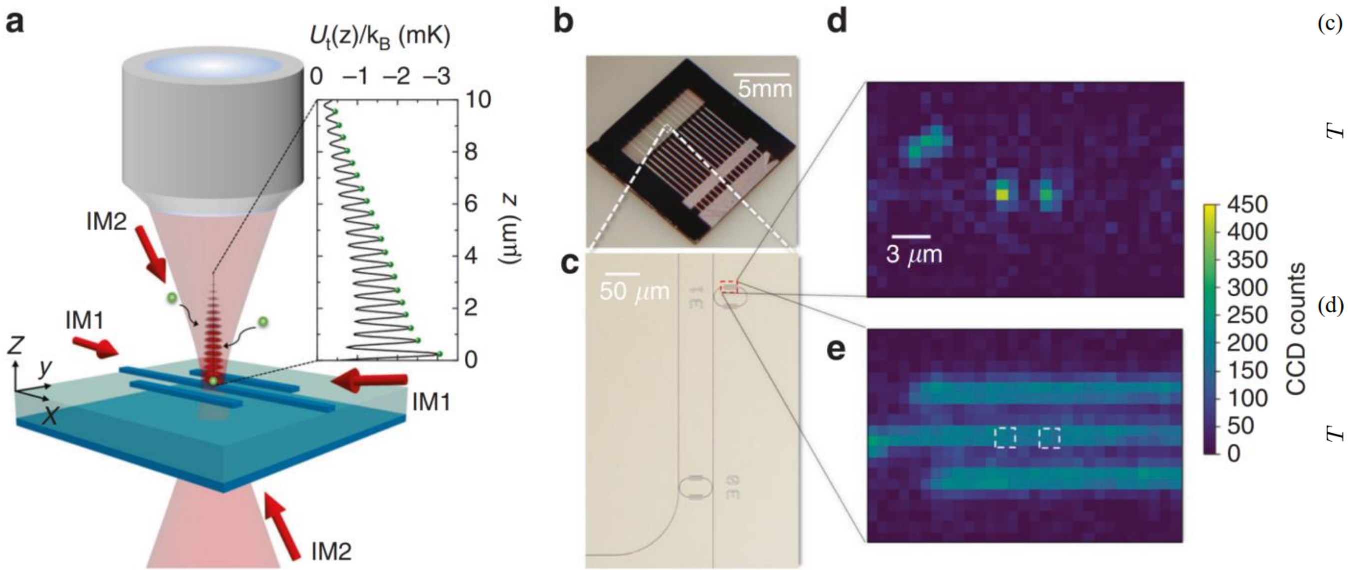


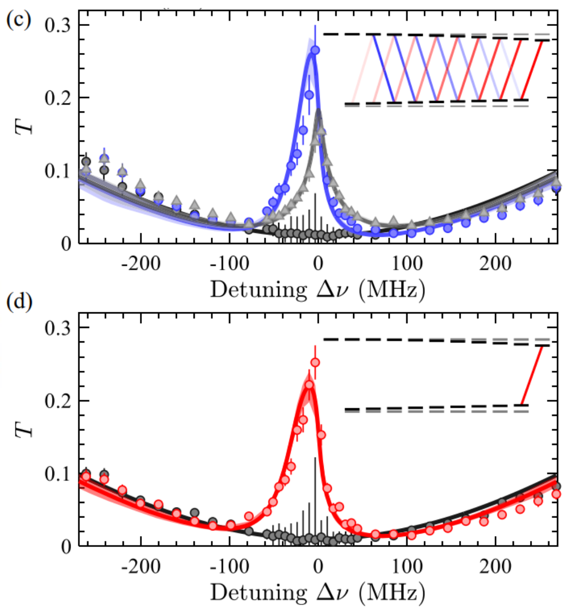


E. Will, L. Masters, A. Rauschenbeutel, M. Scheucher, and J. Volz, "Coupling a Single Trapped Atom to a Whispering-Gallery-Mode Microresonator," Phys. Rev. Lett. **126**, 233602 (2021).

芯片上微环腔

光镊形成一个漏斗，导引下落的原子





M. E. Kim, T.-H. Chang, B. M. Fields, C.-A. Chen, and C.-L. Hung, "Trapping single atoms on a nanophotonic circuit with configurable tweezer lattices," Nat. Commun. **10**, 1647 (2019).

Part 4

我们的实验进展

Our Experimental Progress

实验挑战与解决方案

挑战1: 近场原子俘获

原子需要在距表面 ~100 nm 处被稳定俘获，面临 Casimir-Polder 吸引力和表面吸附问题。

挑战2: 高效光耦合

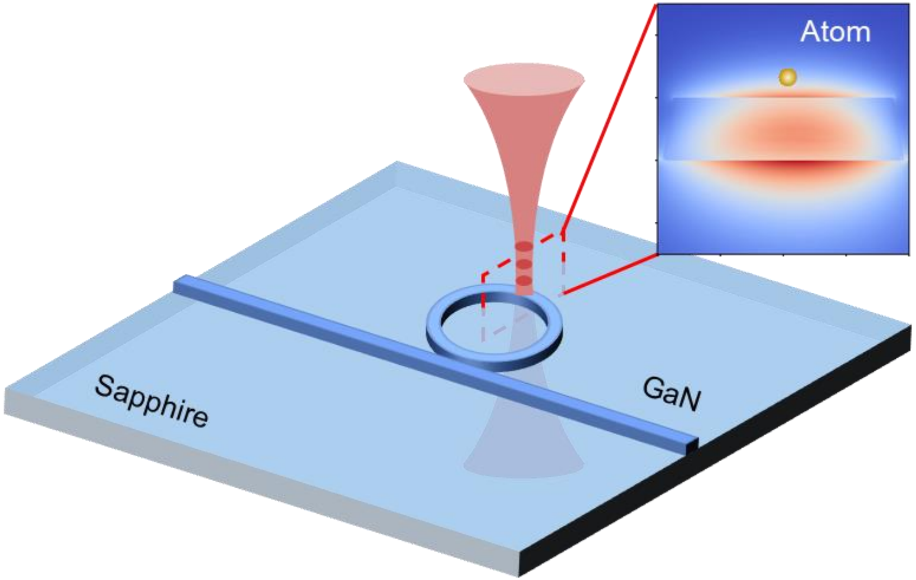
需要将外部光高效耦合进入纳米光子结构，同时实现宽带工作以覆盖多个原子跃迁。

挑战3: 真空兼容性

光子芯片需要在超高真空环境中工作，同时允许激光冷却和 MOT 操作。

挑战4: 单原子成像

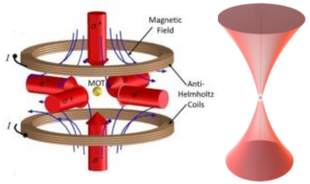
纳米光子器件的散射光会干扰单原子荧光成像。

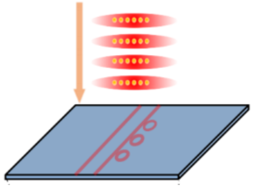


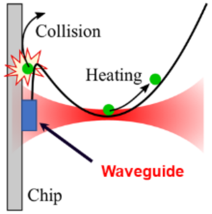
GaN-on-sapphire chip

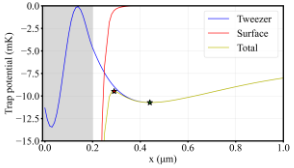
合作：项国勇教授、徐磊、王凌潇

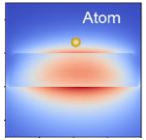
实验步骤











Magneto-optical trap
Optical tweezer

Transport atoms towards the chip

Dynamics of single atoms near the chip surface

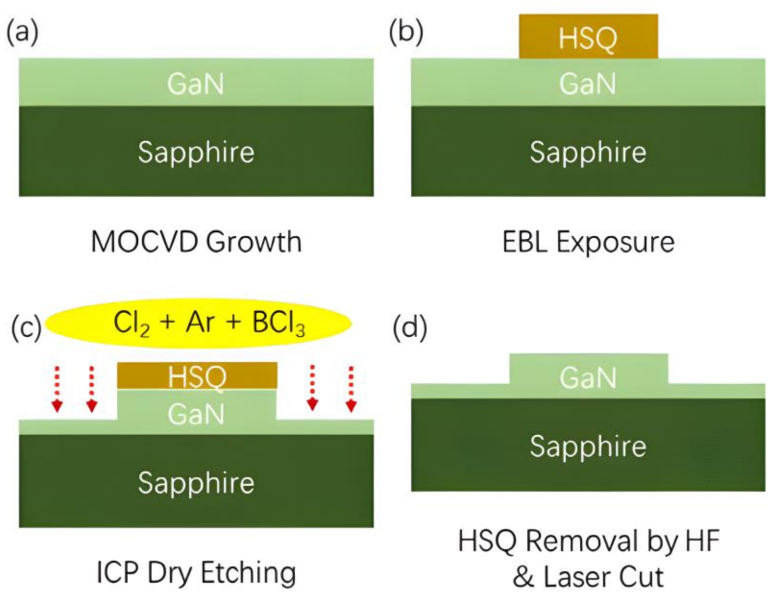
Trapping and interfacing single atoms with the evanescent field

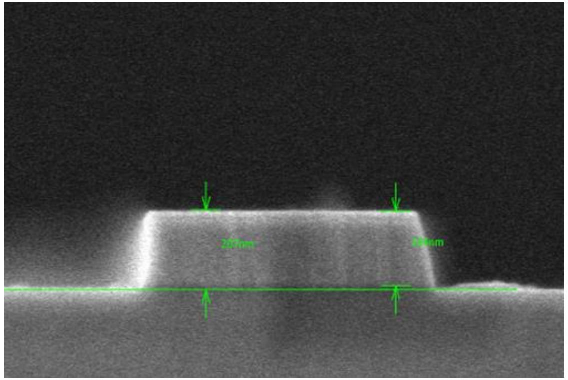
hundreds μm | **< 100 μm** | **< 10 um** | **<1um**

Distance to the chip surface

实验步骤：1. 准备

Electron-beam lithography

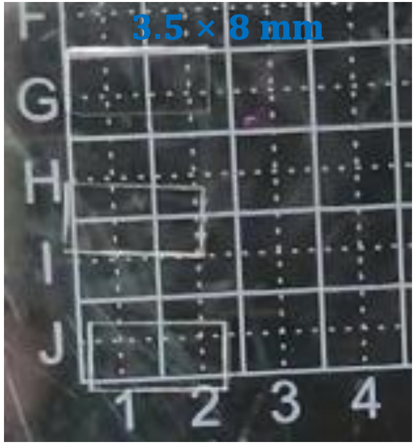




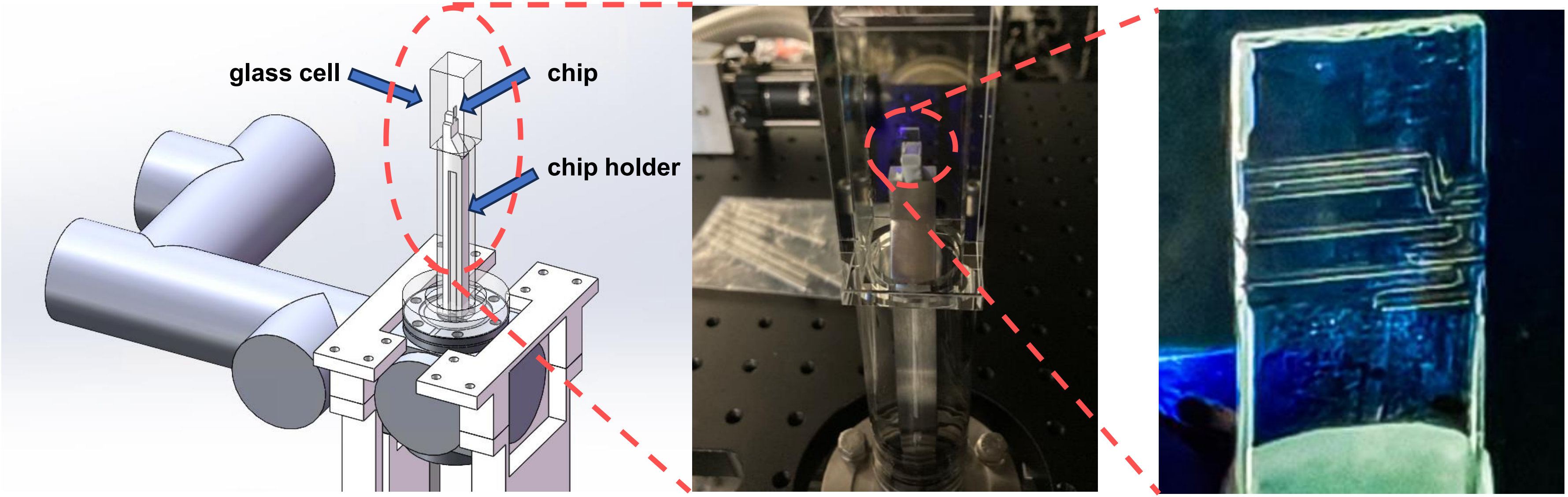
Nanostructure cross section

200 × 700 nm

Transparent chip sample

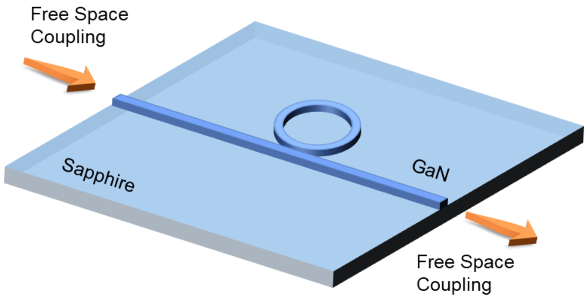


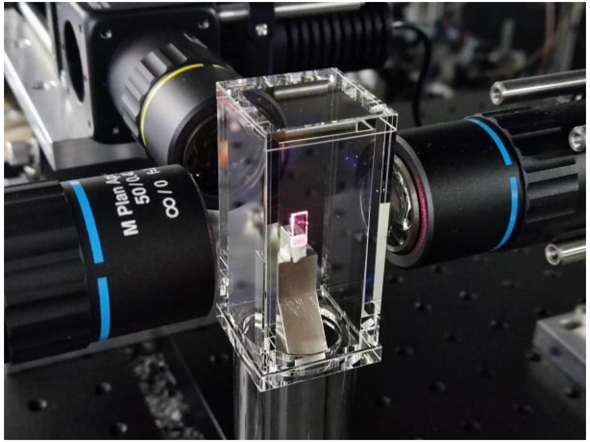
实验步骤：1. 准备

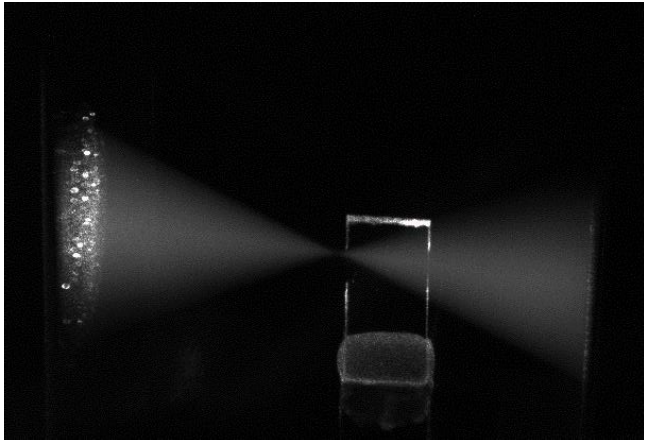


- The chip is adhered to a metal holder for mechanical stability.
- Vacuum pressure maintained at 5×10^{-10} mbar.

实验步骤：1. 准备

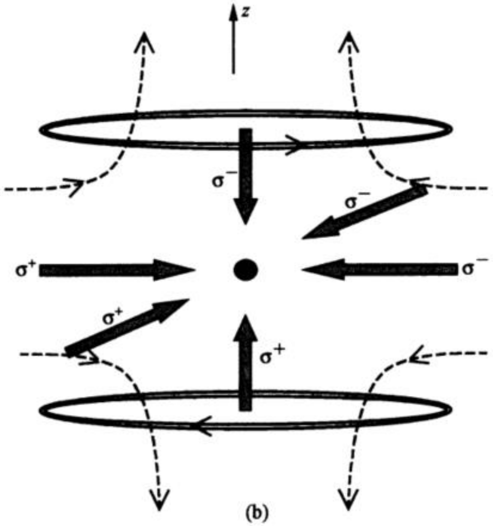


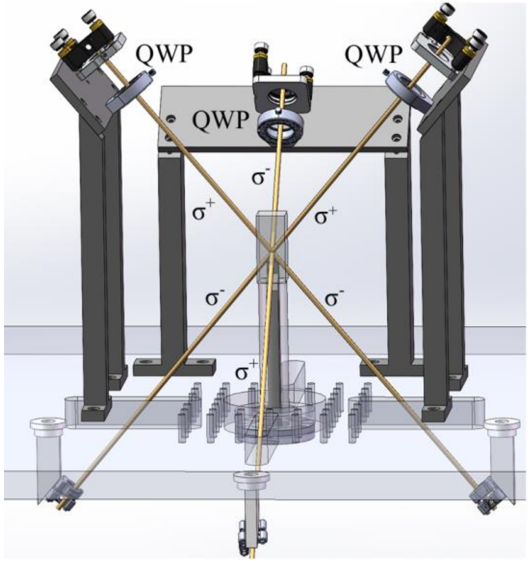


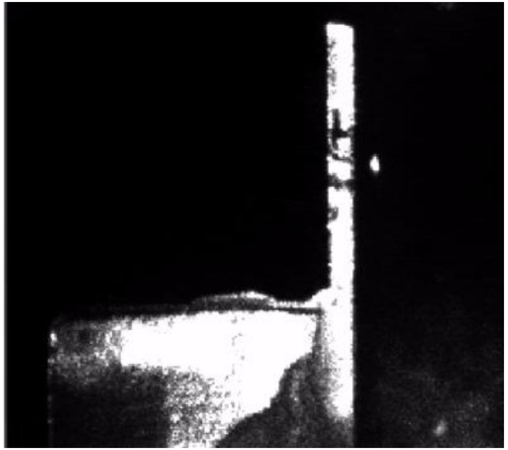


- **Free space coupling.**
- **NA = 0.43 (corrected for 3.5 mm glass wall).**
- **We use background fluorescence for the calibration.**

实验步骤：1. 准备

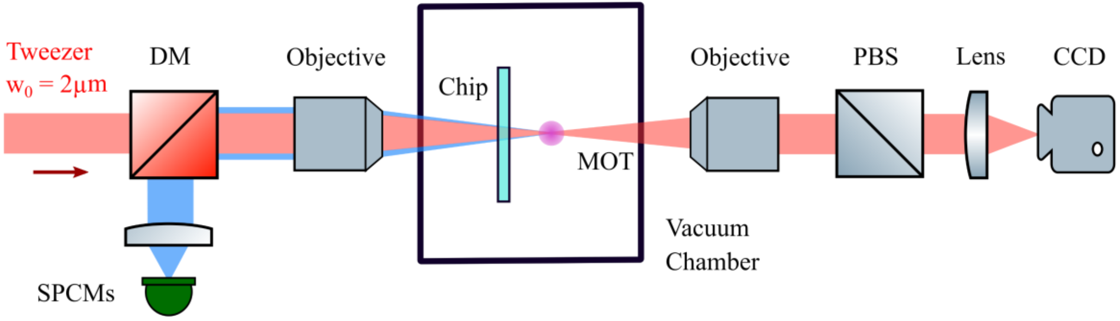


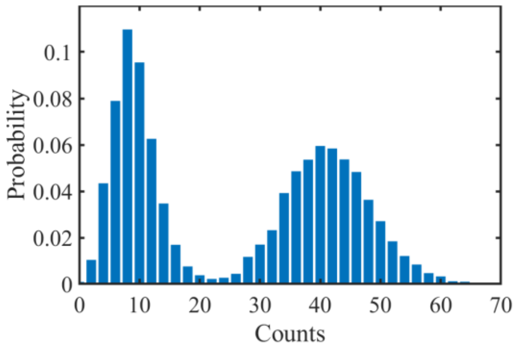


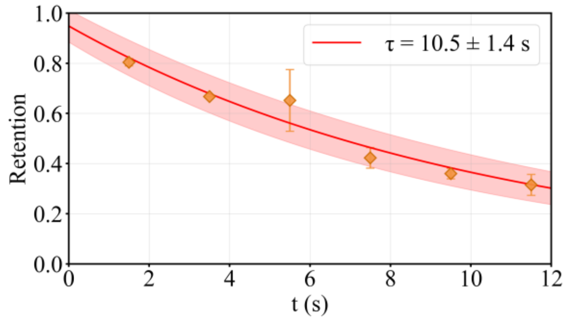


- Modified MOT configuration allows for full optical access around the glass cell.
- MOT temperature: 50 μK.
- MOT distance to the chip surface: 0.3 ~ 1 mm.

实验步骤：1. 准备

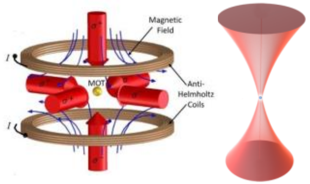




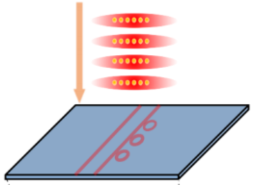


- **The optical tweezer is incident from the backside of the chip.**
- **Single atoms are trapped and imaged about 600 μm away from the chip surface.**
- **The trap lifetime is about 10 s.**

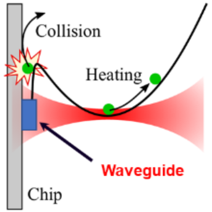
实验步骤



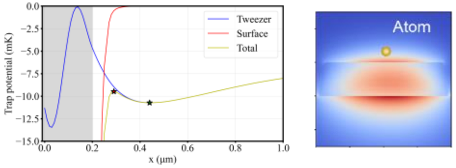
Magneto-optical trap
Optical tweezer



Transport atoms towards the chip



Dynamics of single atoms near the chip surface



Trapping and interfacing single atoms with the evanescent field

hundreds μm

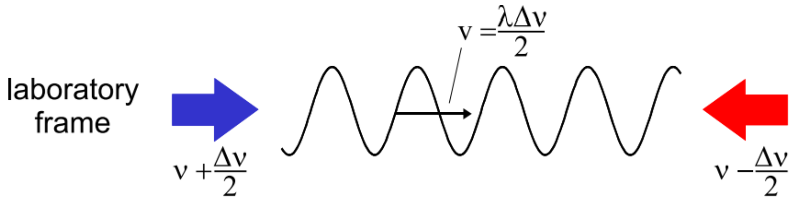
< 100 μm

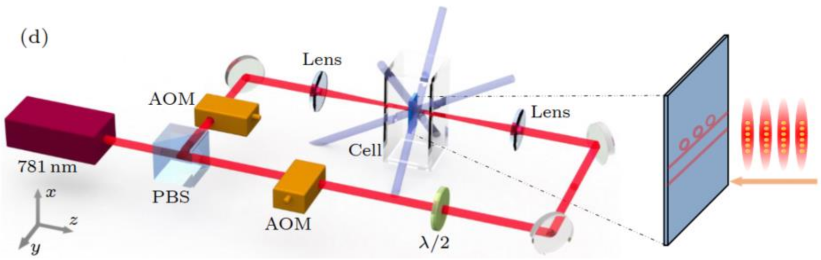
< 10 um

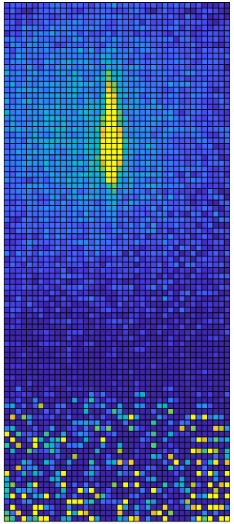
<1um

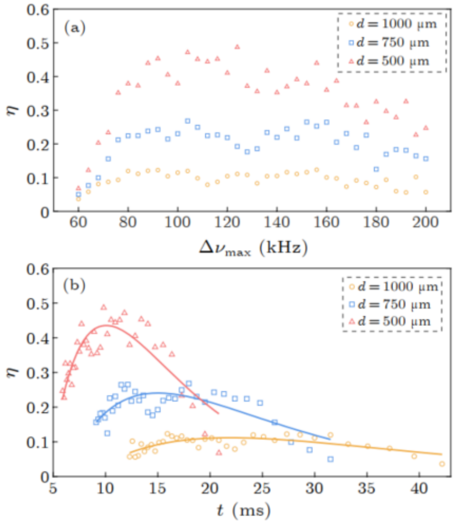
Distance to the chip surface

实验步骤：2.一万纳米





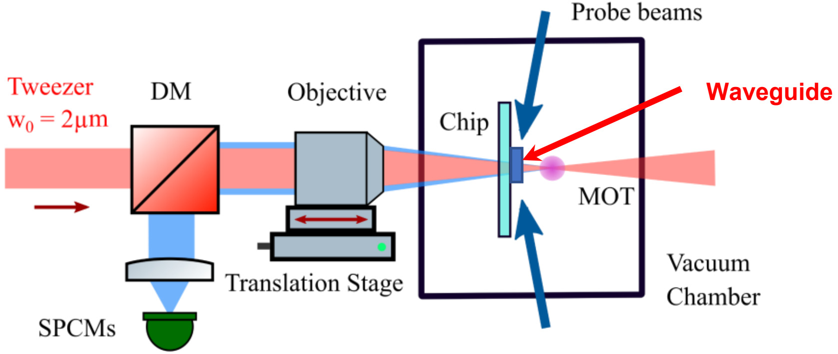


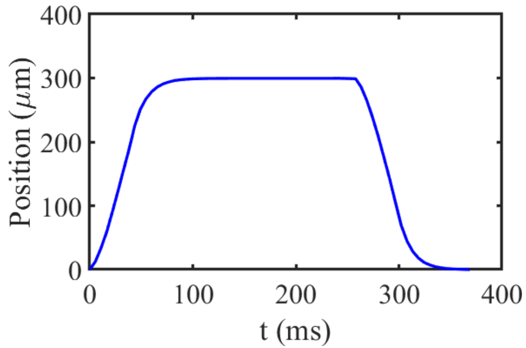


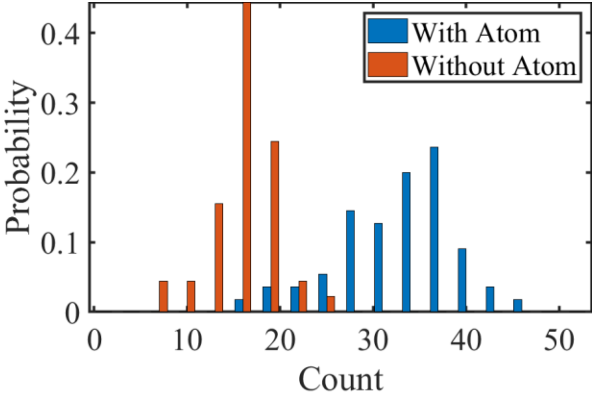
- The conveyor belt is controlled by two phase locked radio frequency signal.

- We use absorption imaging to observe the moving atoms.
- The transport distance is larger than 500 μm.

实验步骤：2.一万纳米



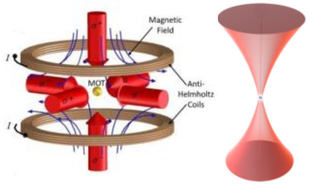




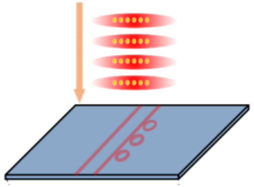
20 μm from the chip surface

- **The objective is mounted on a motorized translation stage with positioning accuracy less than 200 nm.**
- **Single atoms are moved towards the chip back and forth.**
- **We use a pair of probe beam to detect single atoms near chip surface.**

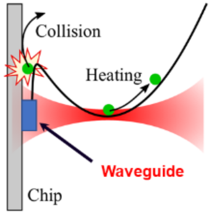
实验步骤



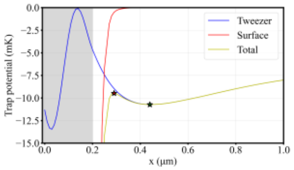
Magneto-optical trap
Optical tweezer

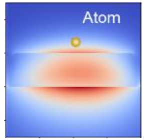


Transport atoms towards the chip



Dynamics of single atoms near the chip surface



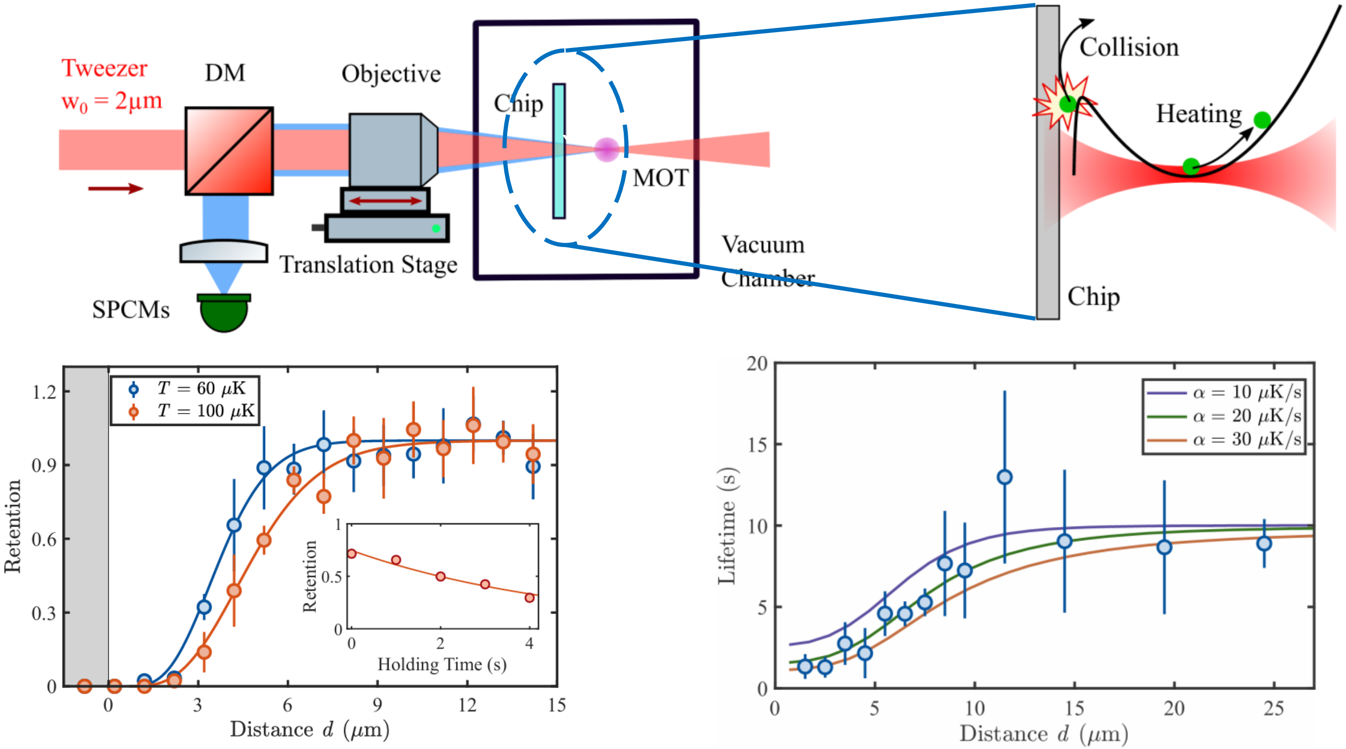


Trapping and interfacing single atoms with the evanescent field

hundreds μm | < 100 μm | < 10 um | <1um

Distance to the chip surface

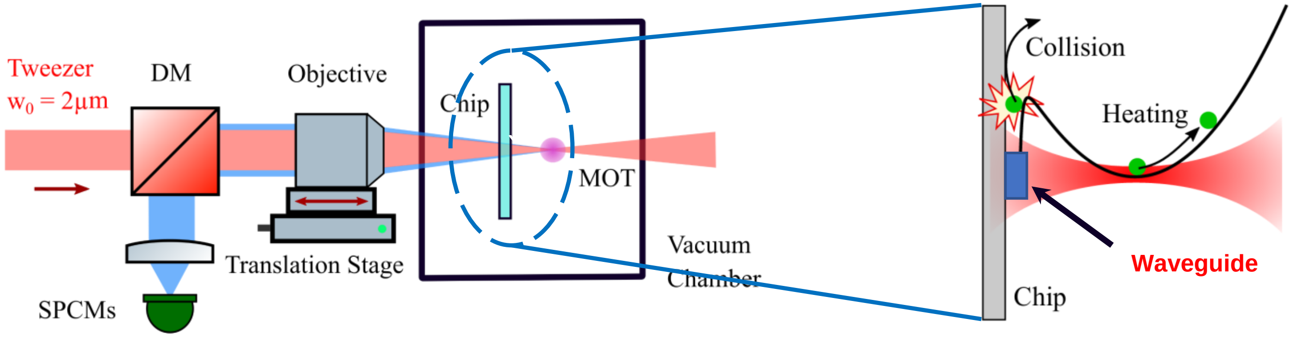
实验步骤：3. 一千纳米

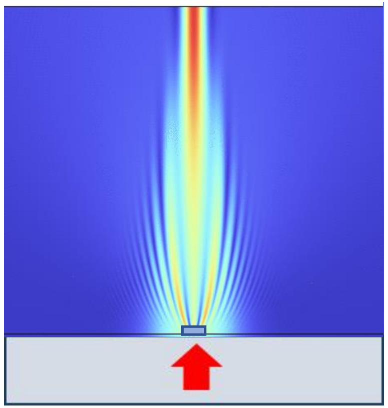


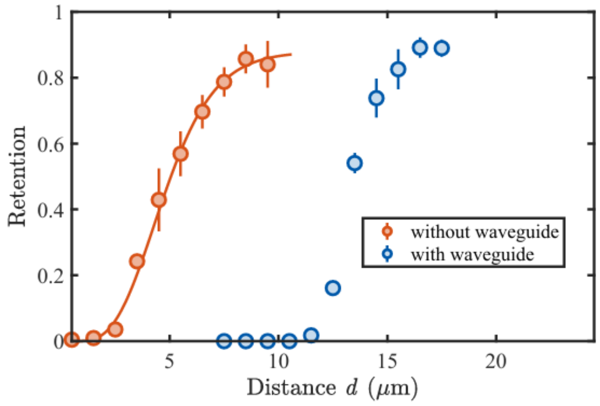
Surface evaporation leads to single-atom loss and reduced trap lifetime.

L. Xu et, al Phys. Rev. Applied 24, 024002 (2025)

实验步骤： 3.一千纳米



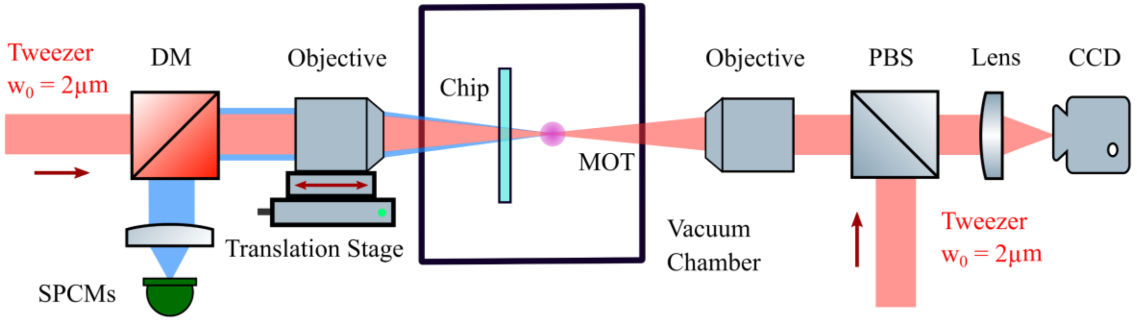




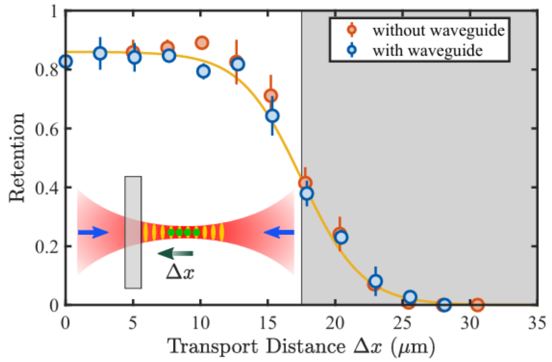
Diffraction effects leads to attraction to the chip surface at larger distance.

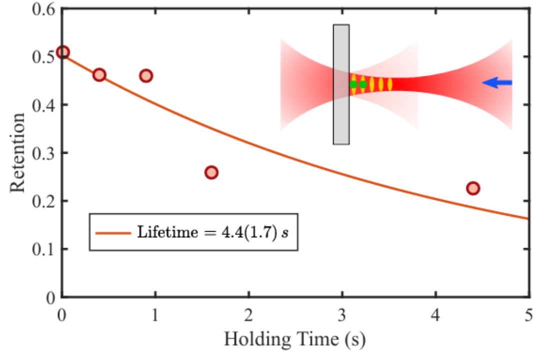
L. Xu et, al Phys. Rev. Applied 24, 024002 (2025)

实验步骤： 3.一千纳米



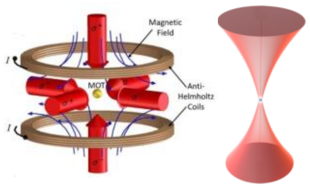
We introduce a standing wave tweezer when single atoms get close to the chip.



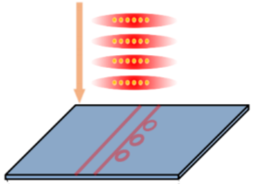


L. Xu et, al Phys. Rev. Applied 24, 024002 (2025)

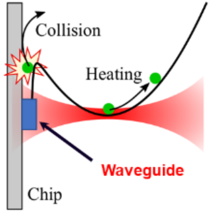
实验步骤



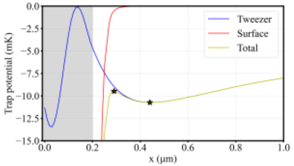
Magneto-optical trap
Optical tweezer

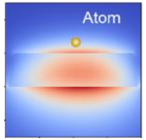


Transport atoms towards the chip



Dynamics of single atoms near the chip surface





Trapping and interfacing single atoms with the evanescent field

hundreds μm

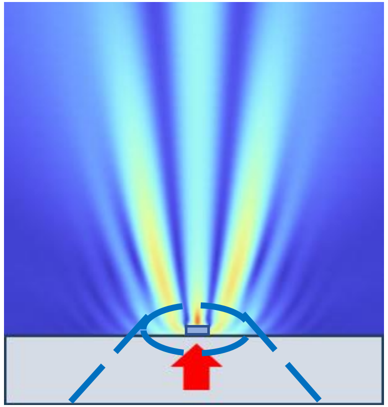
< 100 μm

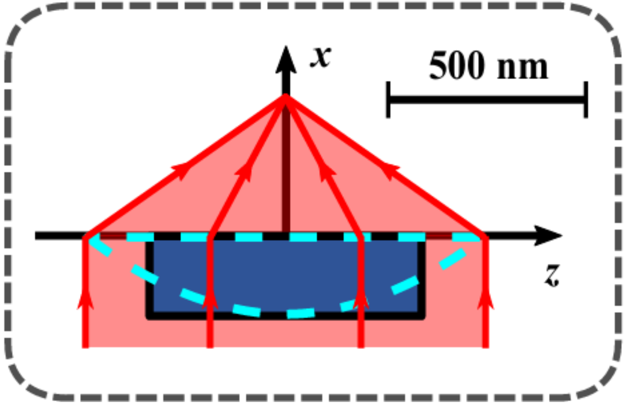
< 10 um

<1um

Distance to the chip surface

实验步骤：4.一百纳米



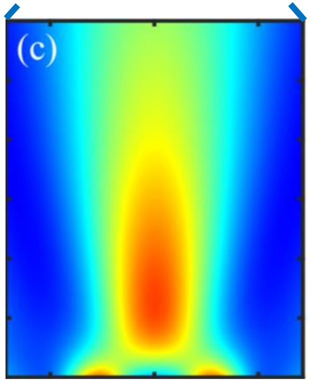


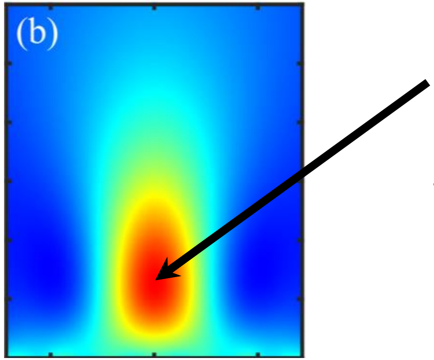
Phase Shift: $U_0(z) = \exp[-i\frac{2\pi(n-1)t}{\lambda}\frac{2z^2}{a^2}].$

Angular Spectrum Method:

$$U(z,x) = \frac{1}{4\pi^2}\iint \mathcal{F}(U_0)\left(\frac{k_z}{2\pi}\right)e^{i(k_z z + k_x x)}\mathrm{d}k_z,$$

$$k_x = \sqrt{(\frac{2\pi}{\lambda})^2 - k_z^2}.$$



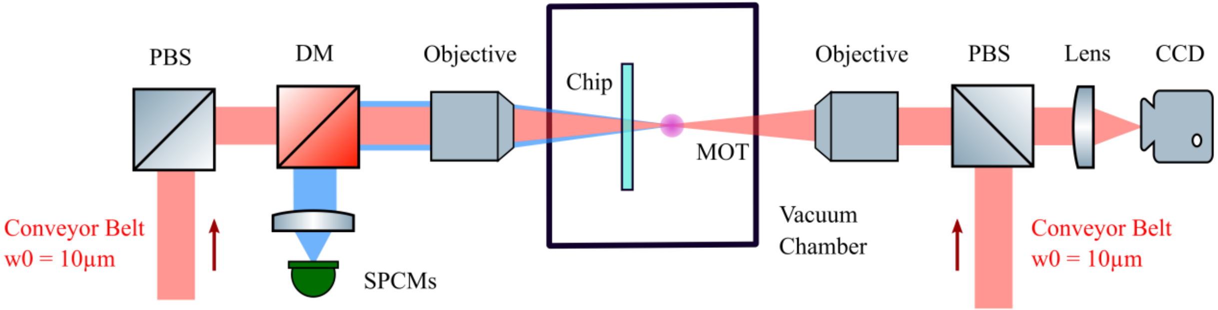


Focal length: 260 nm

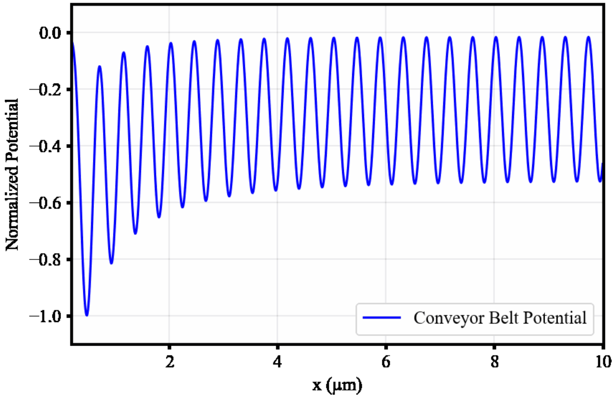
We expect

- **Trapping single atoms at the lens focal.**

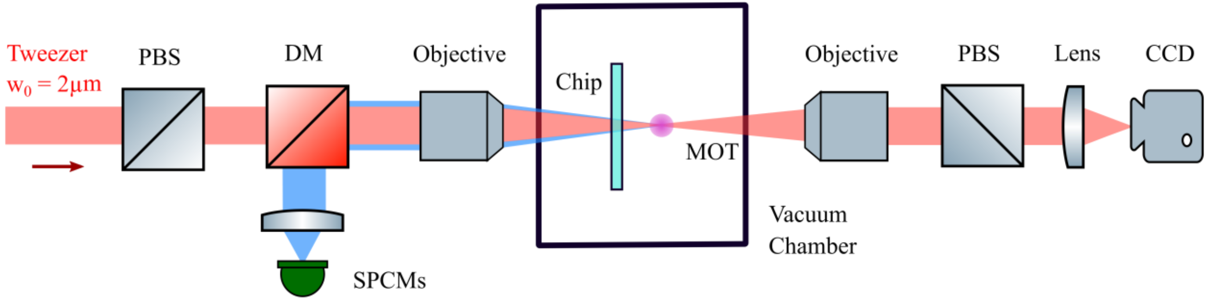
实验步骤：4.一百纳米



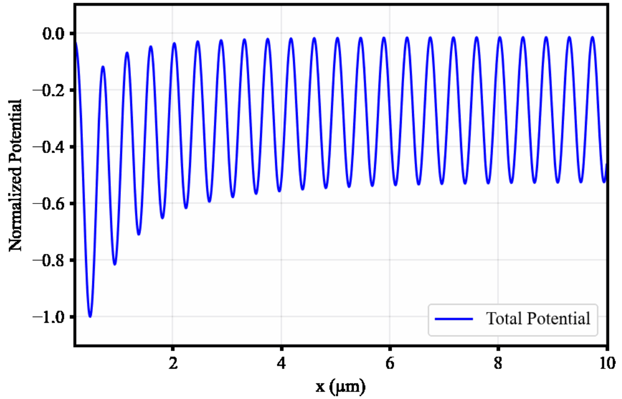
- **Atoms are first transferred to the chip surface with the optical conveyor belt.**



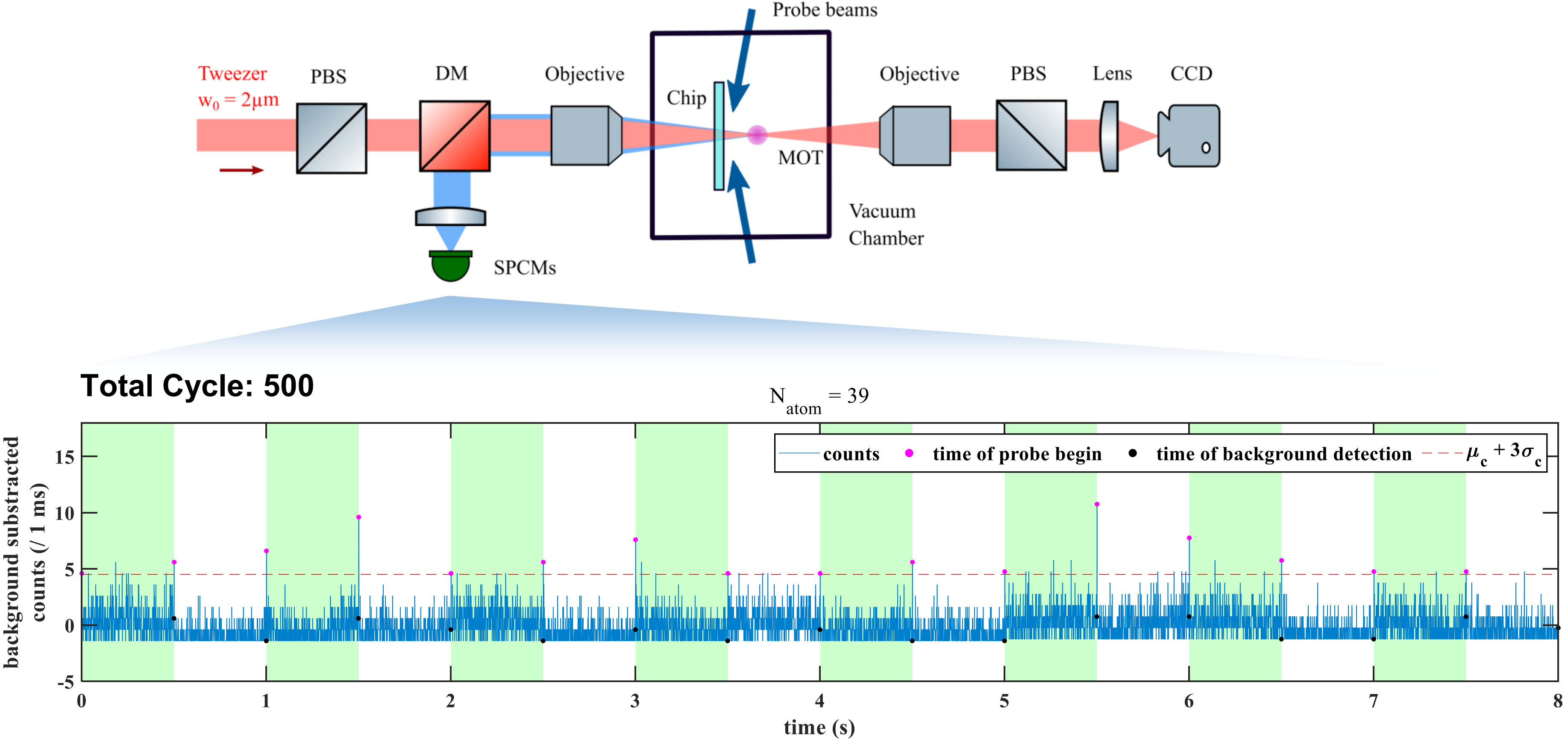
实验步骤：4.一百纳米



- Atoms are first transferred to the chip surface with the optical conveyor belt.
- Single atoms are then probabilistically loaded into the tight trap formed by lens effects.

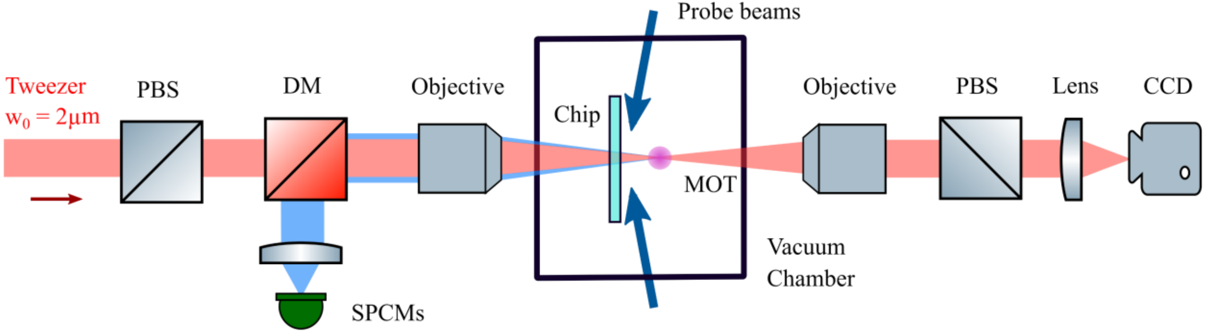


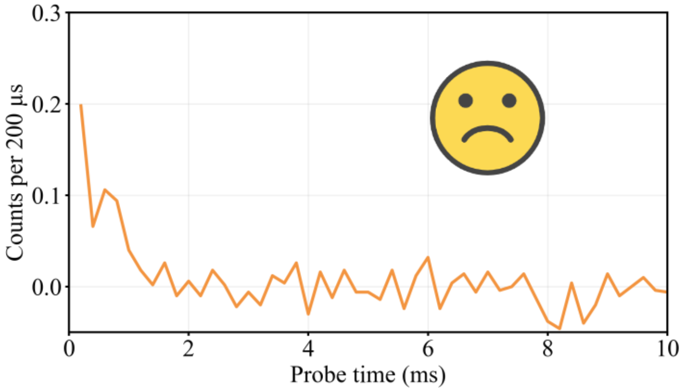
实验步骤：4.一百纳米

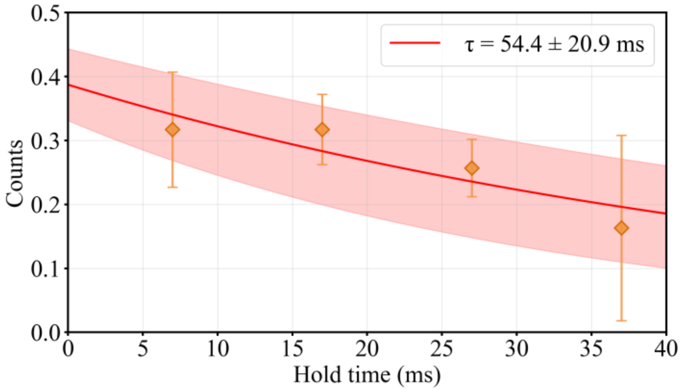


Probe beams
Tweezer
w0 = 2μm
PBS
DM
Objective
Chip
MOT
Objective
PBS
Lens
CCD
Vacuum Chamber
SPCMs
Total Cycle: 500
N atom = 39
counts
time of probe begin
time of background detection
μc + 3σc
background substracted counts (/ 1 ms)
time (s)

实验步骤：4.一百纳米

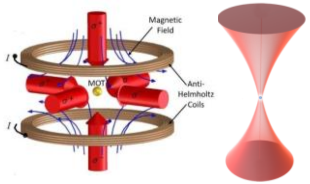




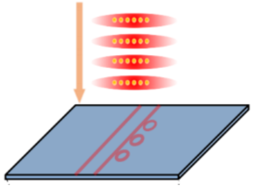


- **PGC cooling does not works for our setup.**
- **The trap lifetime is about 54 ms.**

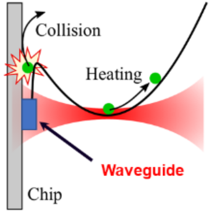
实验步骤



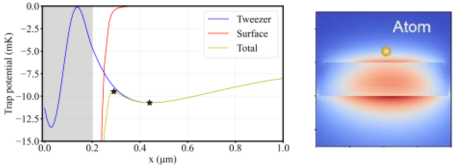
Magneto-optical trap
Optical tweezer



Transport atoms towards the chip



Dynamics of single atoms near the chip surface



Trapping and interfacing single atoms with the evanescent field

hundreds μm

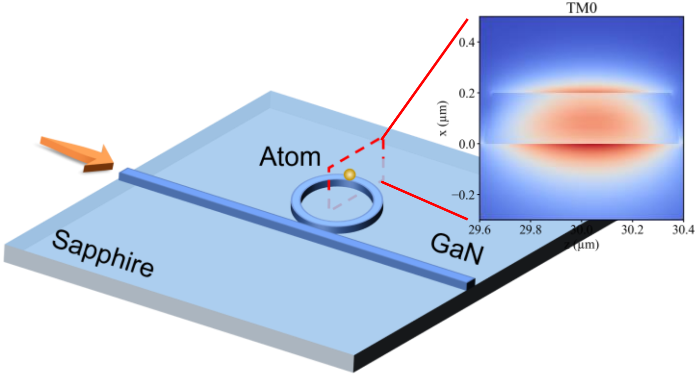
< 100 μm

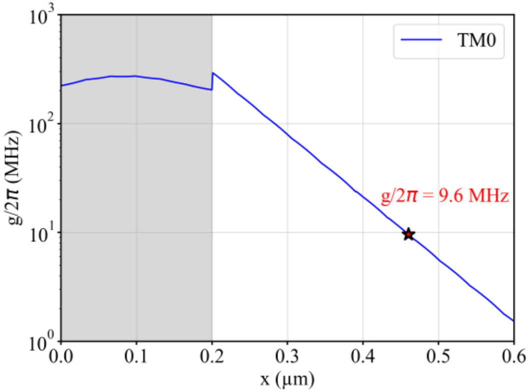
< 10 um

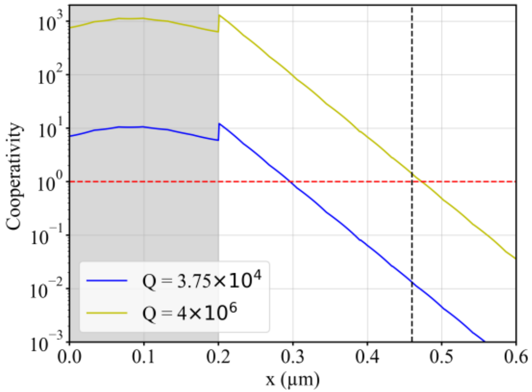
<1um

Distance to the chip surface

下一步计划







$w = 700\ nm, h = 200\ nm, r = 30\ \mu m$

- **For ^{87}Rb D2 transition:**

$\omega = 2\pi \times 384.5$ THz

$d = 1.7 \times 10^{-29}$ C/m

$Q = 3.75 \times 10^{4}$

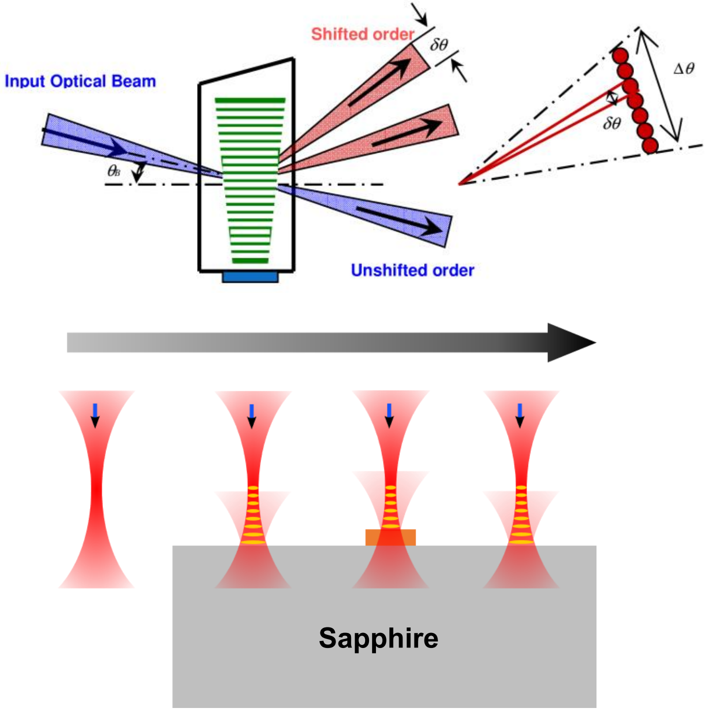
$$g = \sqrt{\frac{\omega d^2}{2\hbar\epsilon_0 V_m}}$$

$$C = \frac{3\lambda^3}{4\pi^2}\frac{Q}{V_m}$$

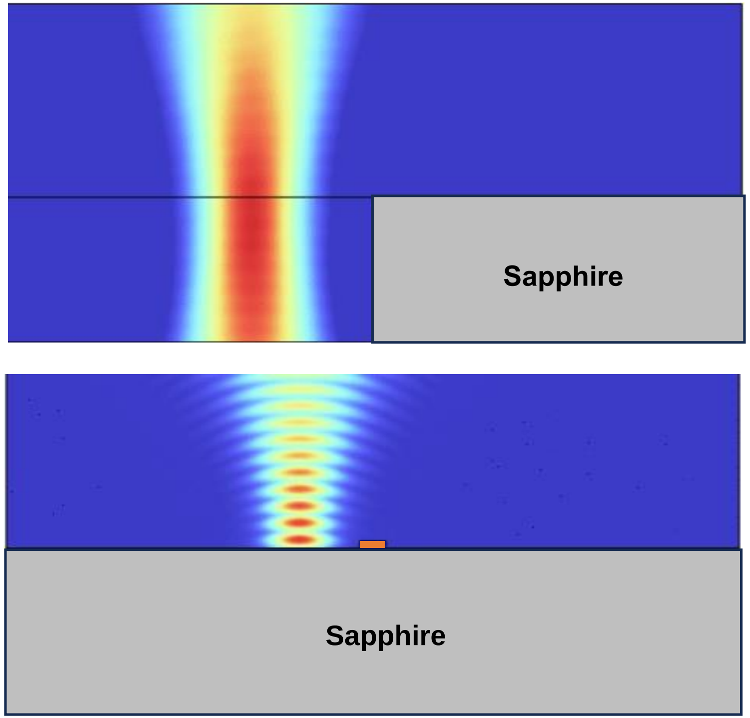
- **For our cavity quality factor, we are now far away from strong coupling regime.**
- **With state-of-the-art cavity ($Q = 4 \times 10^6$), it is promising to reach strong coupling regime.**

下一步计划

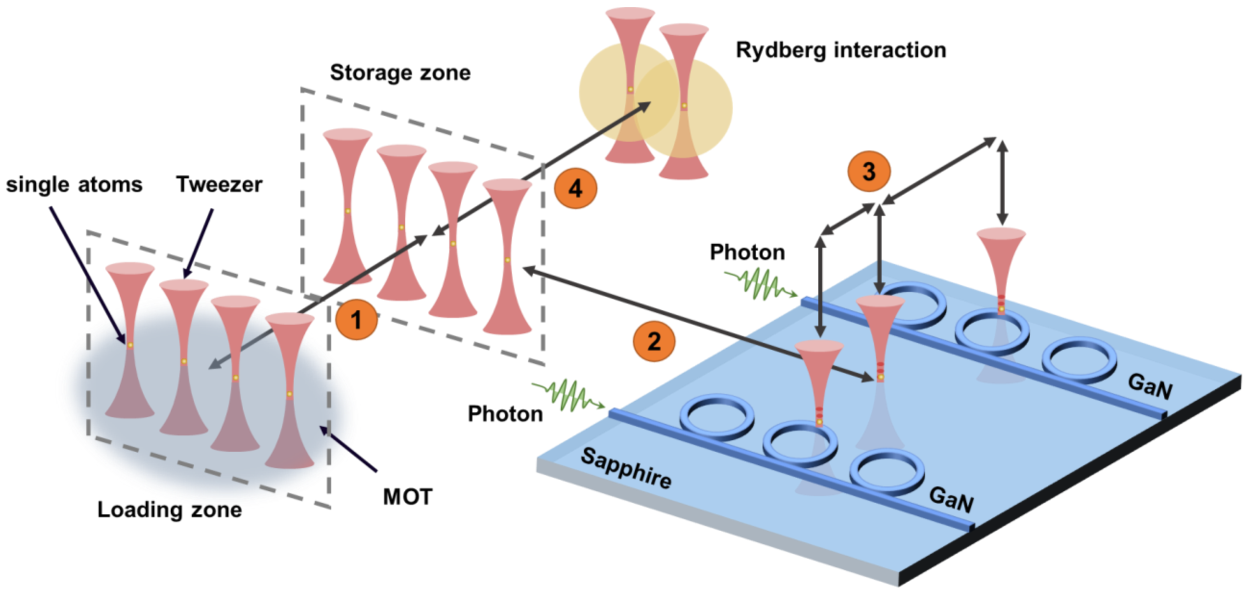
Tweezer transport with AODs



Simulation of tweezer potential



下一步计划



- Atoms can be loaded and moved to the storage zone from a MOT.
- Atoms can be moved among the photonic chip surface to interact with different photons.
- Atoms can be moved away from the chip to implement Rydberg-mediated interactions.

Part 5

总结与展望

Summary and Future Directions

课程要点总结

1 腔QED基础

Jaynes-Cummings模型描述原子-光子相互作用

强耦合条件: $g \gg \kappa, \gamma$

真空Rabi分裂是强耦合标志

2 发展历程

1963年JC模型 → 1987年实验验证

微波腔 & 光学腔两大技术路线

2012年诺贝尔物理学奖

3 集成光子优势

超小模式体积增强耦合 ($g \propto 1/\sqrt{V}$)

天然集成能力，可扩展性强

CMOS兼容，可批量制造

4 主要平台与应用

微环腔、光子晶体波导、瓶状微腔

量子网络、分布式量子计算

单光子源、量子传感

📝 核心公式回顾

$C = g^2/(\kappa\gamma)$ $g \propto d\cdot\sqrt{(\omega/V_{eff})}$

更多应用场景

量子计算接口

连接多个小型量子处理器，构建**模块化量子计算机。**

- 原子阵列量子比特
- 光子互连链路
- 分布式量子门操作

克服单处理器规模限制

确定性单光子源

利用腔增强的Purcell效应，实现高效率**按需单光子发射。**

- 高纯度单光子态
- 高收集效率 (>90%)
- 不可区分光子

量子通信和线性光学量子计算

量子传感

原子与纳米光子结构结合，实现**超灵敏探测。**

- 电/磁场传感
- 光学原子钟同步
- 引力波探测辅助

突破经典传感极限

未来发展方向

待解决的技术挑战

进一步提高原子俘获效率和稳定性

延长原子在近场的相干时间

实现确定性单原子装载

多原子阵列

构建一维/二维原子阵列与光子晶体结构耦合，探索多体量子光学效应。

电信波段转换

使用Yb-171等原子实现电信波段直接操作，兼容现有光纤网络。

商业化路径

开发标准化量子光子接口芯片，推动量子网络产业化。

长期愿景

全球量子互联网

分布式量子超算

绝对安全通信

超精密时钟网络

谢谢聆听

Questions & Discussion

推荐阅读

Reiserer & Rempe, Rev. Mod. Phys. (2015)   Haroche & Raimond, "Exploring the Quantum"   Chang et al., Rev. Mod. Phys. (2018)