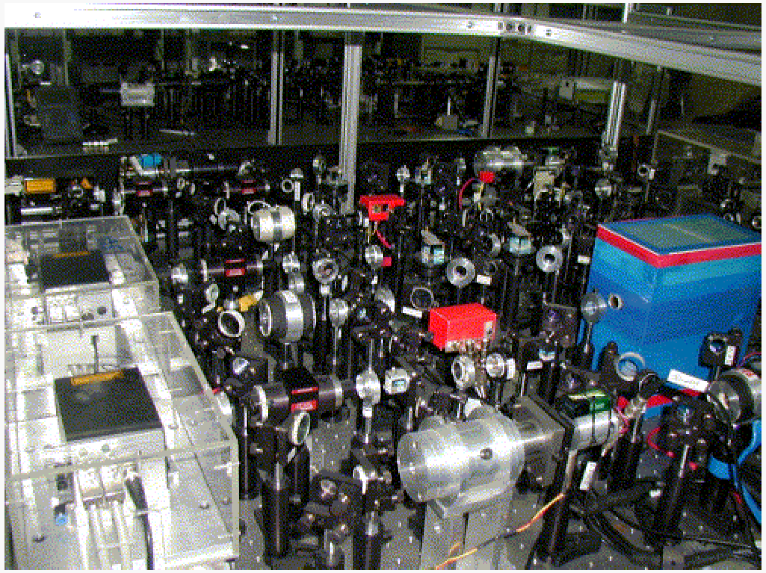
On Chip Photonics and Optoelectronics

祝世宁

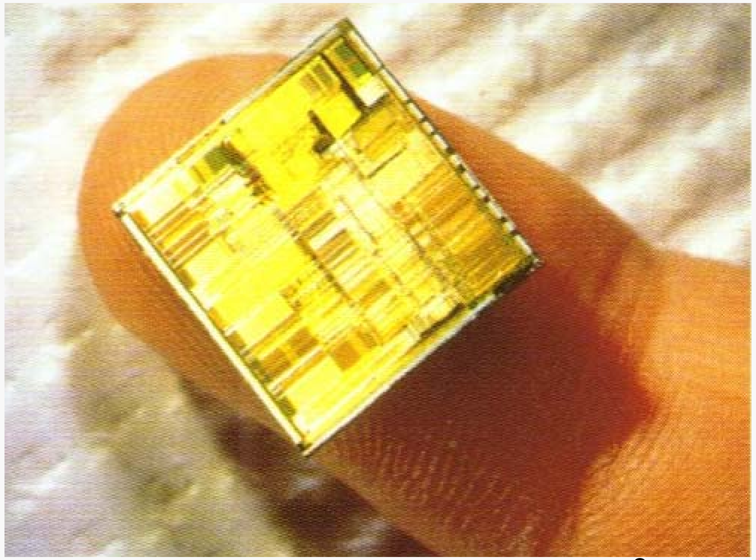
National Laboratory of Solid State Microstructures

Nanjing University



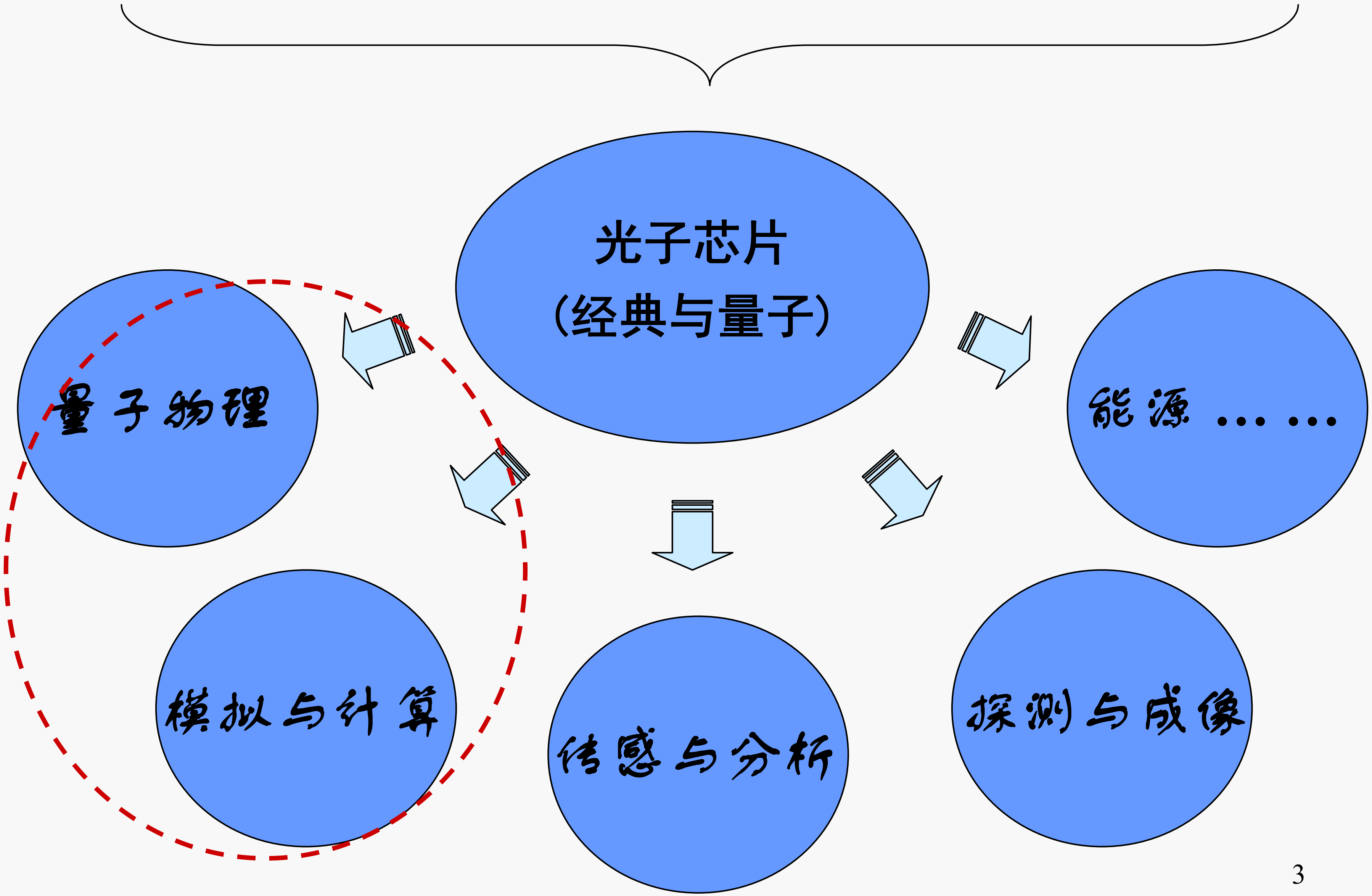
光子芯片
（经典与量子）

1945, MIT

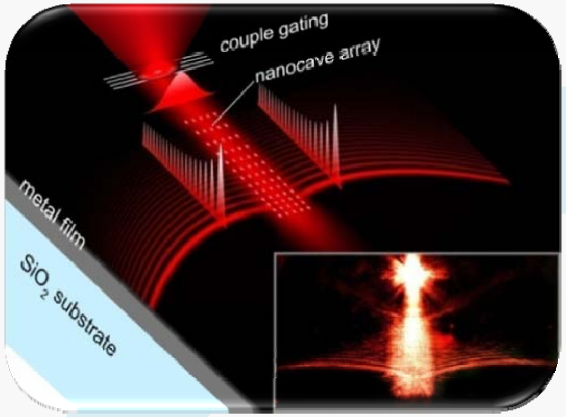


1996, Intel

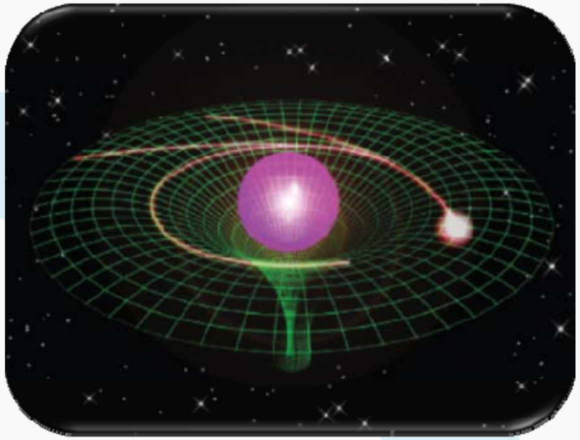
集成光学、SPP、微腔、光子晶体、量子点、量子线、……



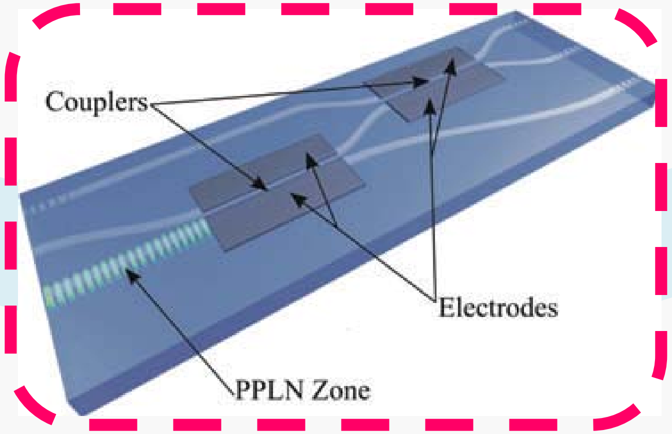
SPP 光子集成及量子芯片



光学模拟芯片

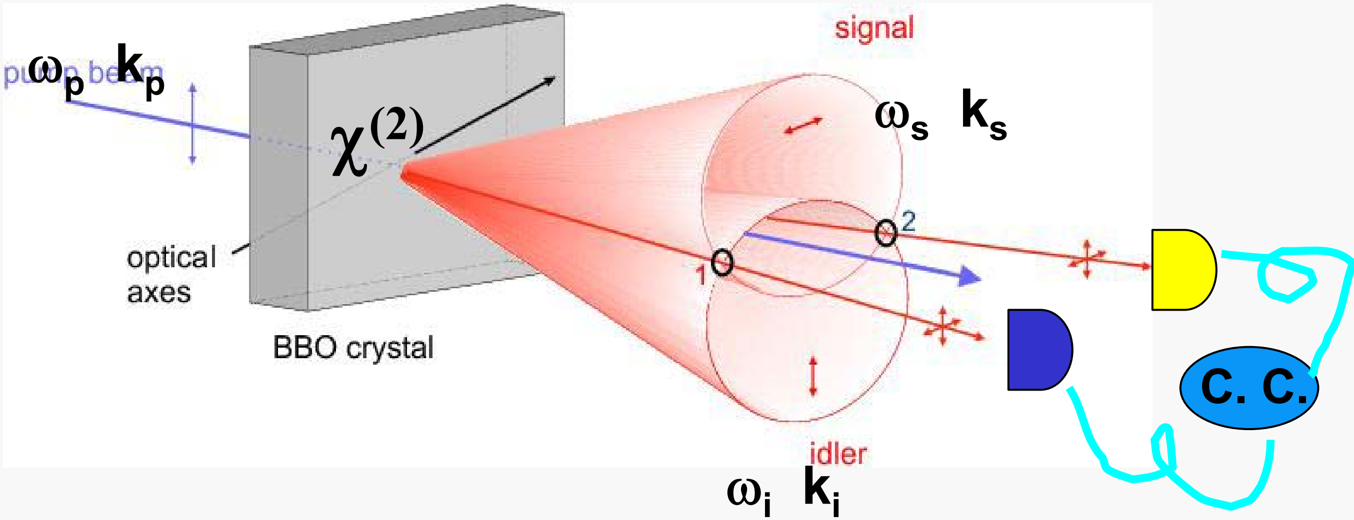


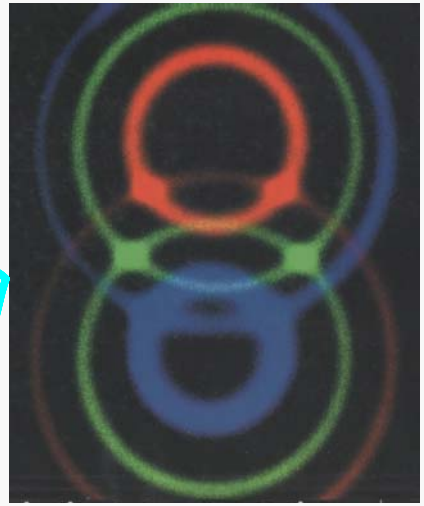
On Chip Photonics & Optoelectronics



LN 集成量子芯片

纠缠光子的产生(自发参量下转换)
Spontaneous parametric down-conversion (SPDC)





$$\omega_p = \omega_s + \omega_i$$

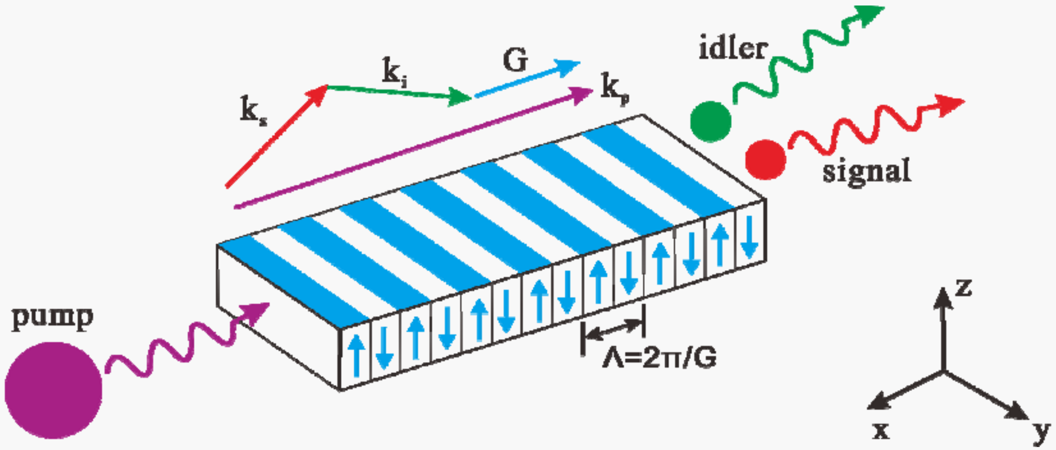
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|V\rangle_1 |H\rangle_2 + |H\rangle_1 |V\rangle_2)$$

$$|\Psi\rangle = \psi_0 \sum_{\vec{k}_i, \vec{k}_s} \delta(\omega_i + \omega_s - \omega_p)\delta(\vec{k}_i + \vec{k}_s - \vec{k}_p)\hat{a}^{+}_{\vec{k}_i}\hat{a}^{+}_{\vec{k}_s}|0\rangle$$

1935 EPR

纠缠光子的产生(自发参量下转换)
Spontaneous parametric down-conversion (SPDC)



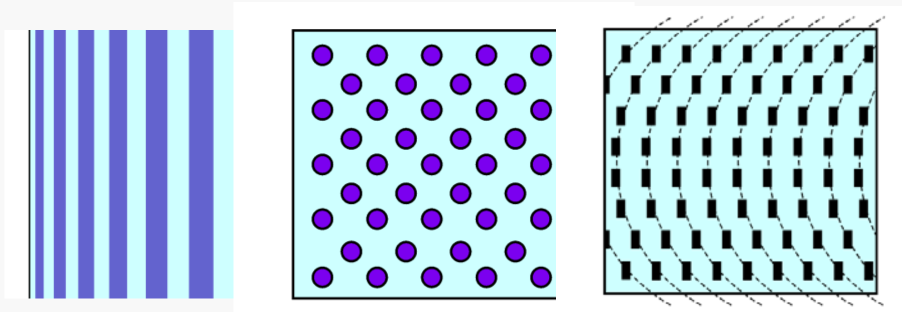
$$\omega_p = \omega_s + \omega_i$$
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

$$\omega_p = \omega_s + \omega_i$$
$$\vec{k}_p = \vec{k}_s + \vec{k}_i + \vec{G}$$

$$|\Psi\rangle = \psi_0 \sum_{\vec{k}_s,\vec{k}_i} \delta(\vec{k}_s + \vec{k}_i + \vec{G} - \vec{k}_p)\hat{a}_s^+ \hat{a}_i^+ |0\rangle$$

$$G_m = \frac{2m\pi}{\Lambda}$$

Different structures



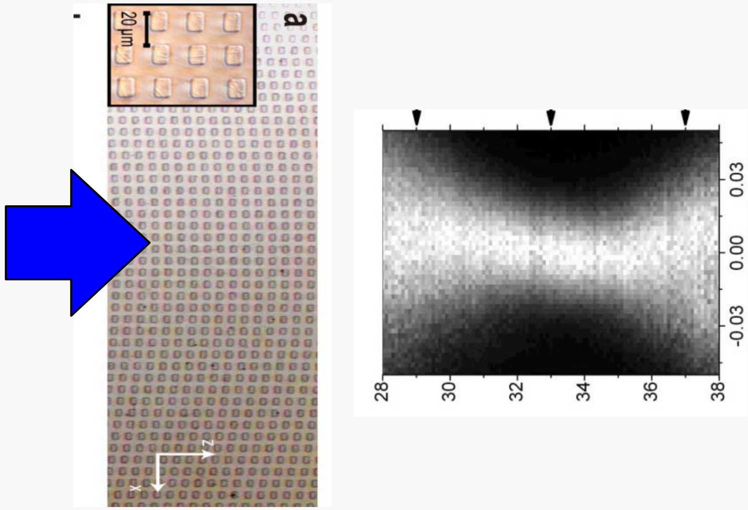
Key features

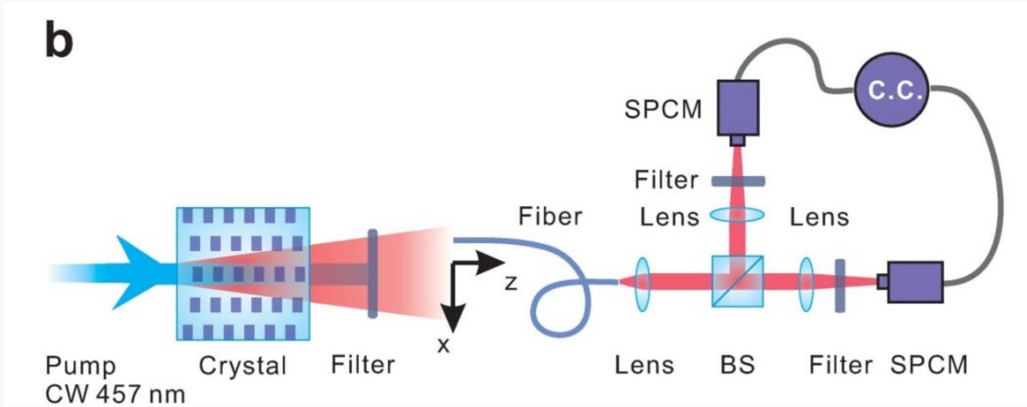
◆High efficiency, 1-2 order higher (bulk), 4-5 orders higher than BPM crystals

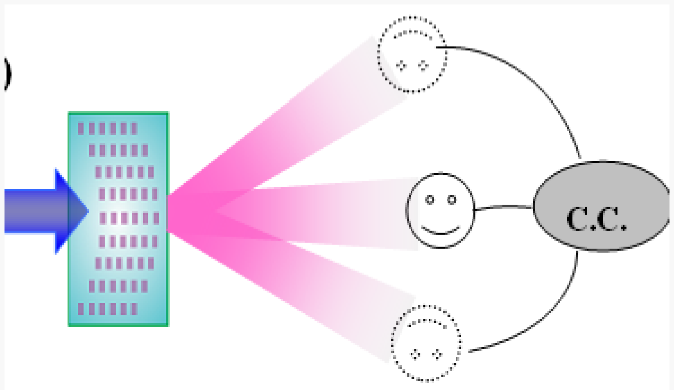
◆Designable wavelength

◆Engineerable state

纠缠光子的产生、分束、聚焦、成像







$$\frac{1}{d_1}+\frac{1}{d_2}=\frac{2}{f_{eff}}$$

$$f_{eff}=\frac{\pi}{g_3\alpha\lambda_p}$$

Leng *et al.*, Nat. Commun. 2, 429 (2011)

P.Xu *et al*, Phys. Rev. A, 86, 013805 (2012)

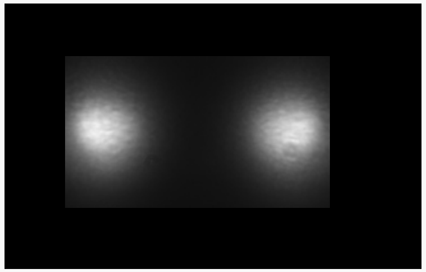
AIP Publishing

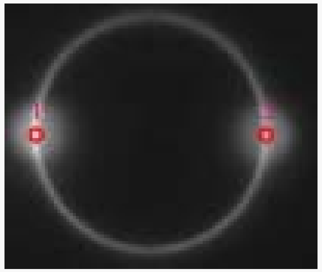
AIP ADVANCES 2, 041401 (2012)

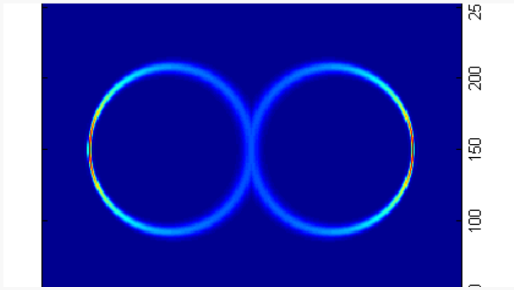
Review Article: Quasi-phase-matching engineering of entangled photons

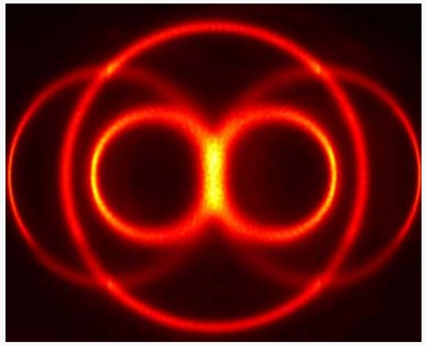
P. Xu[a] and S. N. Zhu[b]
National Laboratory of Solid State Microstructures and School of Physics, Nanjing University, Nanjing 210093, China

(Received 15 August 2012; accepted 17 October 2012; published online 28 December 2012)









可预知单光子多模纠缠 多光子NOON态

Phys. Rev. Lett. 111, 023603 (2013) Phys. Rev. A 86, 023835 (2012)

Research Highlights

Subject Category: Physics

PRL 101, 233601 (2008)

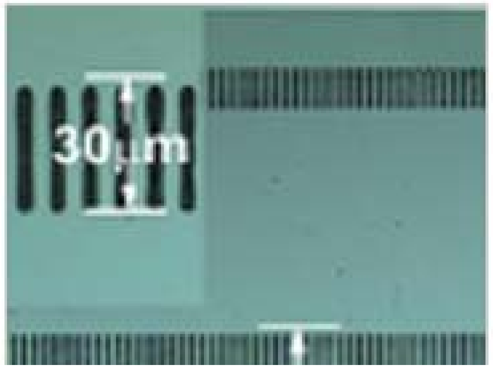
Published online: 17 December 2008 | doi:110.1038/nchina.2008.298

Quantum entanglement: Crystal control

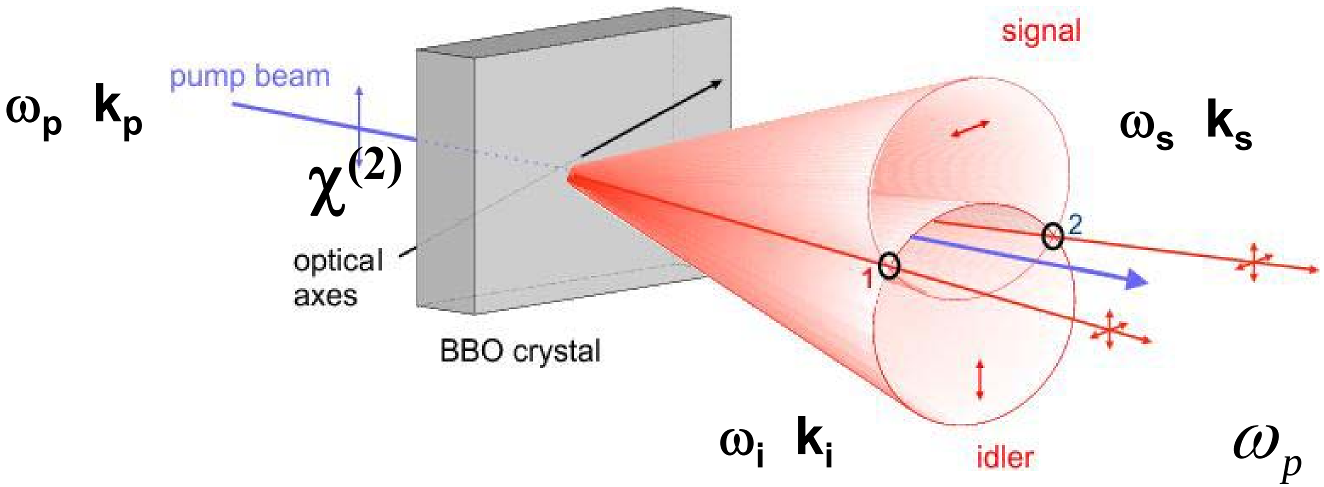
Tim Reid

Researchers in China have shown how to control the properties of entangled photon states using engineered crystal patterns

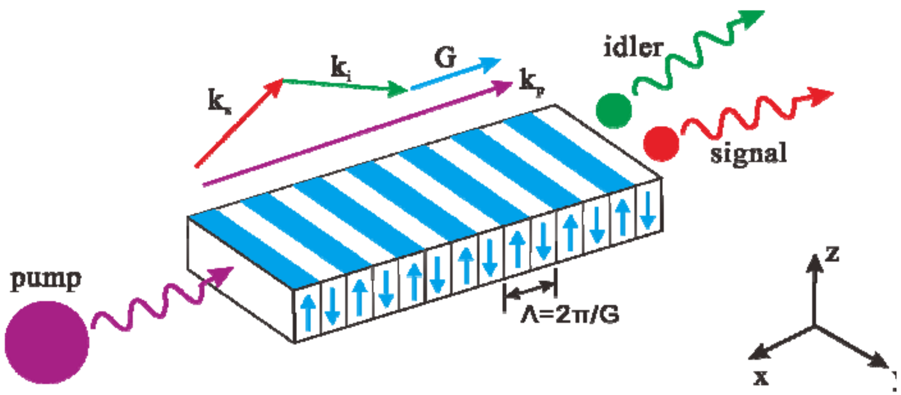
Original article citation
Yu, X. Q. *et al*. Transforming spatial entanglement using a domain-engineering technique. *Phys. Rev. Lett.* **101**, 233601 (2008).



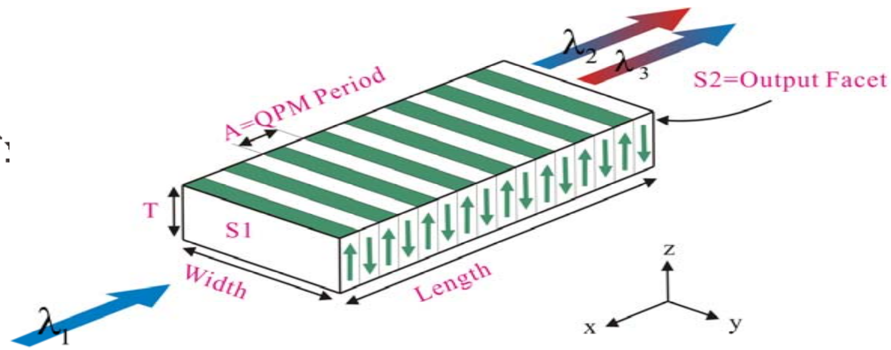
The phenomenon of quantum entanglement, by which two objects are intrinsically linked even when separated by some distance, could have powerful implications for future methods of communication. Shining Zhu at Nanjing University and co-workers[1] have illustrated a way to control the quantum entanglement of two photons by carefully engineering a nonlinear crystal.



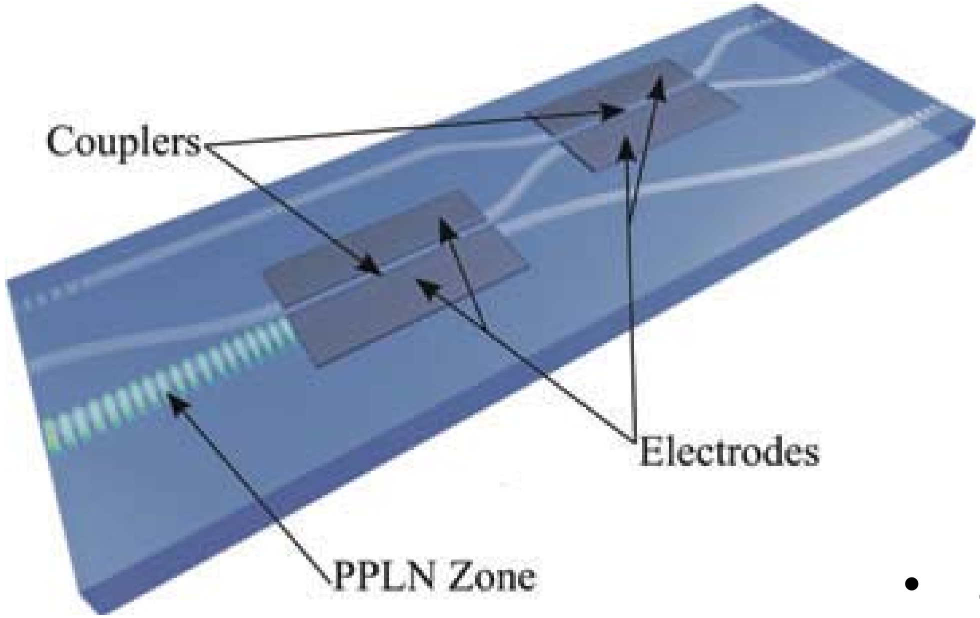
$$\omega_p = \omega_s + \omega_i$$
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$



$$\omega_p = \omega_s + \omega_i$$
$$\vec{k}_p = \vec{k}_s + \vec{k}_i + \vec{G}$$



铌酸锂晶片上分立光学元件的集成及光子芯片的物理实现



Si

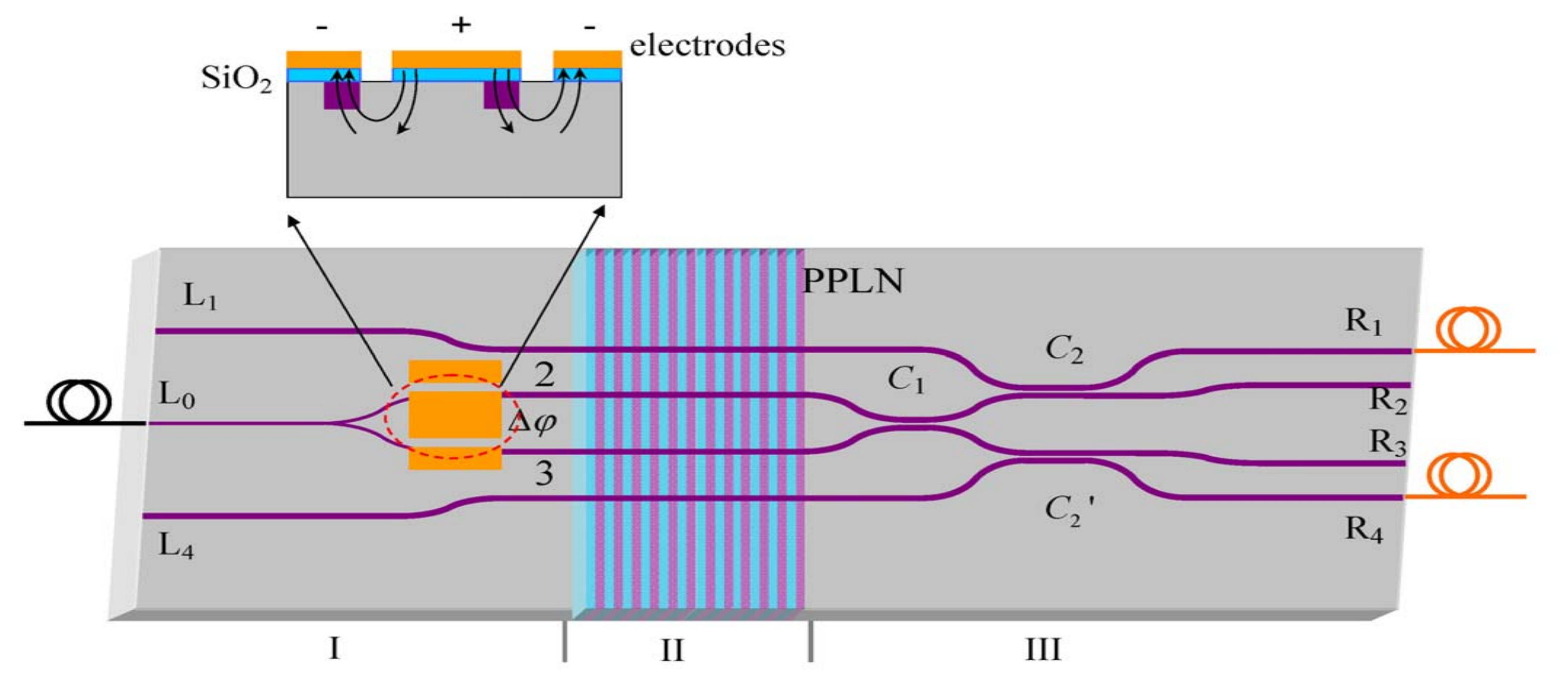
SiO_2

$LiNbO_3$

… …

- 单光子、纠缠光子源 --〉超晶格
- 分束器（光子干涉路径）--〉波导
- 相位控制 --〉电光调制器
- 偏振分束器 --〉定向耦合器
- 偏振旋转器 --〉波片
- 滤波器、分色器 --〉WDM

$LiNbO_3$ 有源光量子芯片

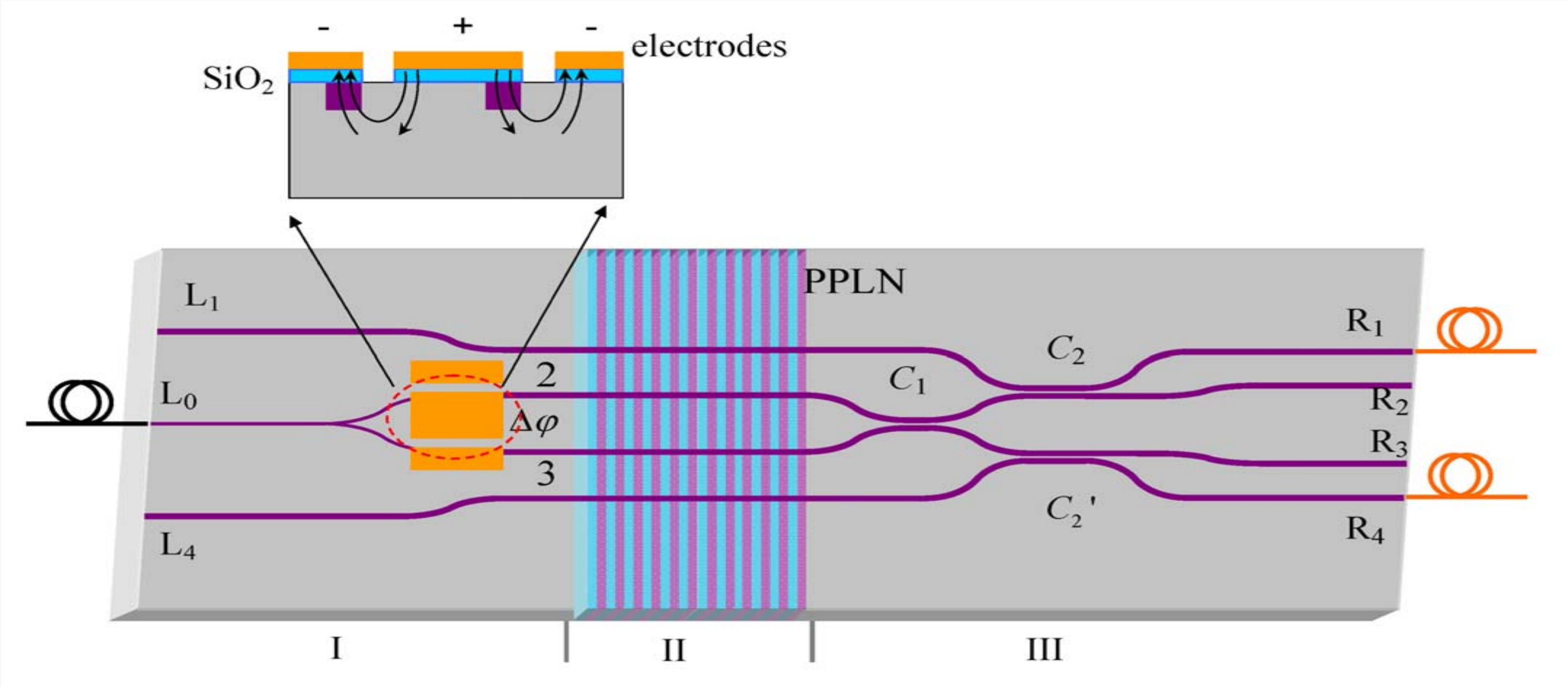


I: A 780 nm pump is coupled into waveguide L_0 and equally distributed by a Y-branch beamsplitter, electro-optic effect controls the phase-shift between two paths.

II: A pair of entangled photons at 1,560 nm are generated from either one of the two PPLN waveguides, yielding a path-entangled state.

III: The quantum interference is realized by a 2×2 directional coupler C_1. By filters C_2, C_2'. Entangled photons are in R1 and R4. The pump is in R2 and R3.

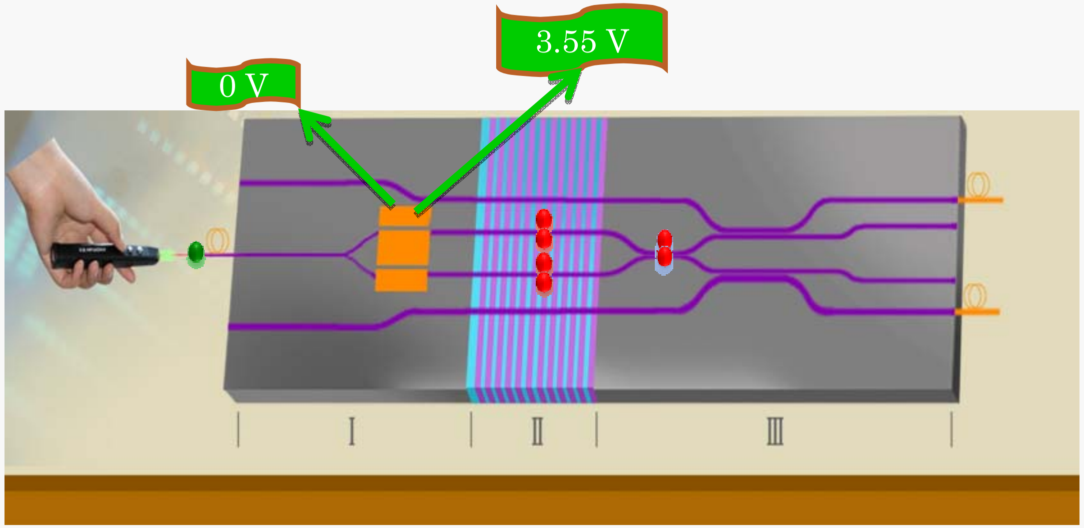
$LiNbO_3$ 有源光量子芯片



$$\frac{1}{\sqrt{2}}\left(|2,0\rangle + e^{i\Delta\varphi}|0,2\rangle\right) \xrightarrow{EOPS} \frac{1}{\sqrt{2}}\left(|2,0\rangle - |0,2\rangle\right)\sin(\Delta\varphi/2) + |1,1\rangle\cos(\Delta\varphi/2)$$

$$|\Psi\rangle_{bunch} = \frac{1}{\sqrt{2}}\left(|2,0\rangle - |0,2\rangle\right)\ (\Delta\varphi = \pi)$$

$$|\Psi\rangle_{sep} = |1,1\rangle\ \ (\Delta\varphi = 0)$$

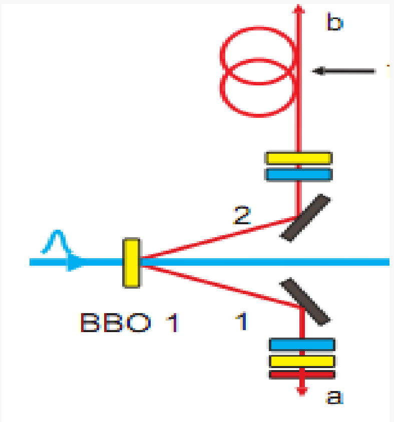


- Stability
- Scalability
- Miniaturization

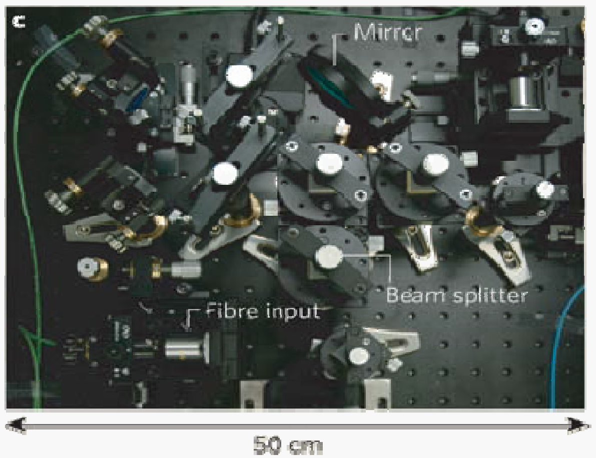
I
Pump region

II
PPLN
(classical → Quantum)

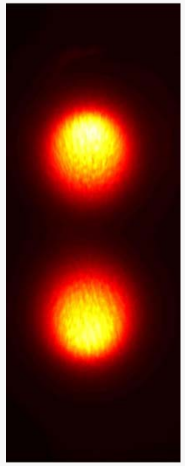
III
Quantum interference



+

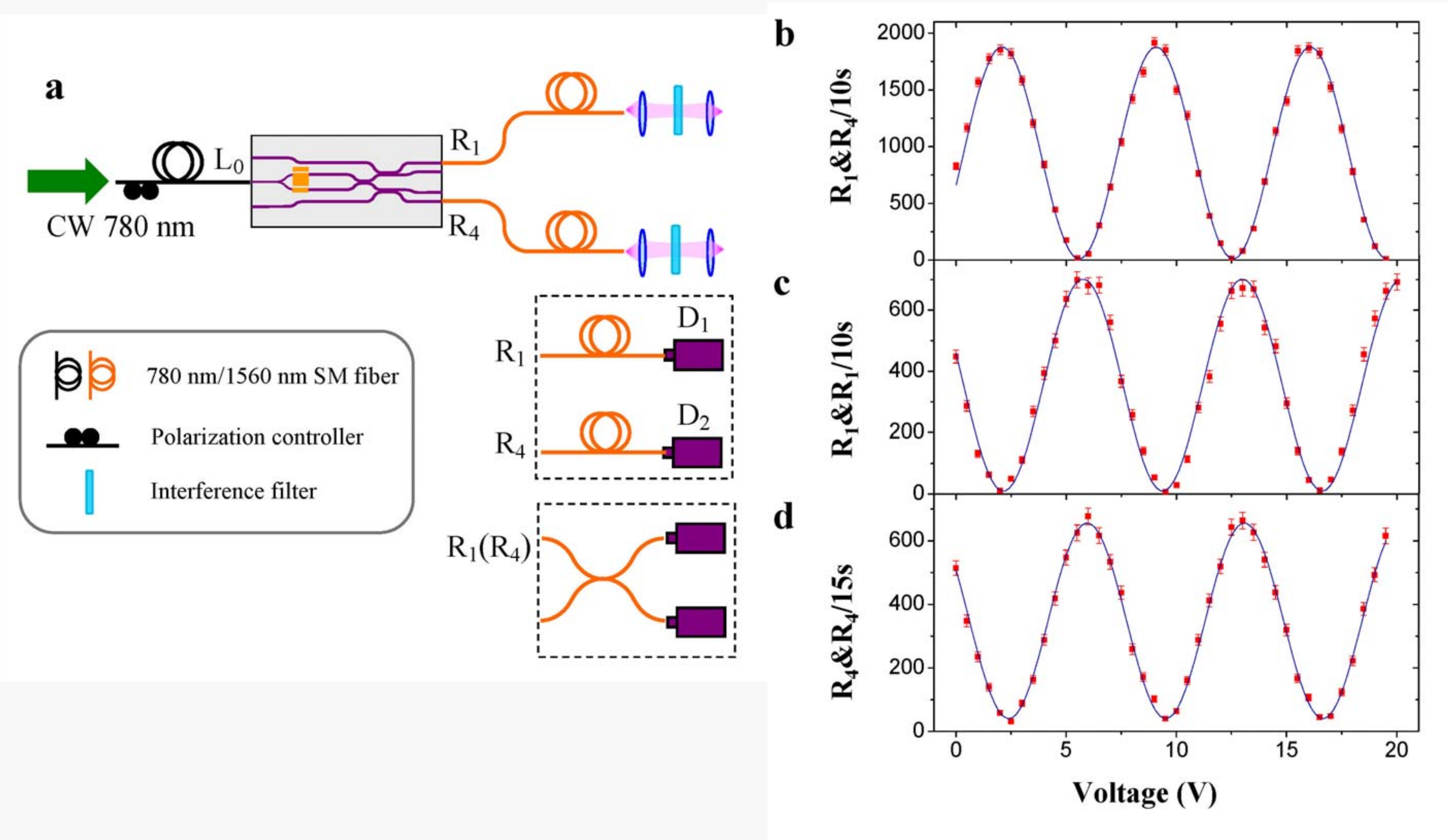


→

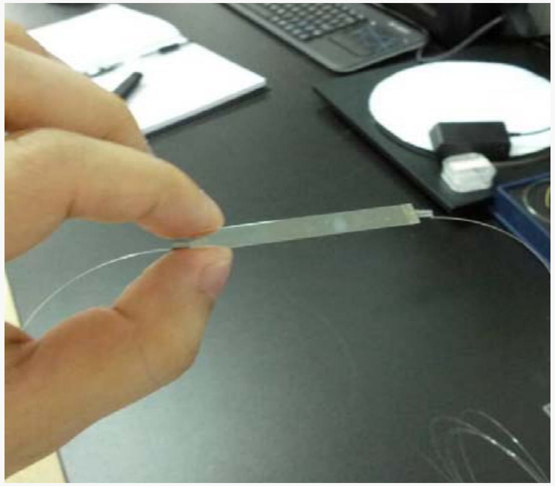


$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|2,0\rangle - |0,2\rangle\right)\sin(\Delta\varphi/2) + |1,1\rangle\cos(\Delta\varphi/2)$$

$LiNbO_3$ 有源光量子芯片

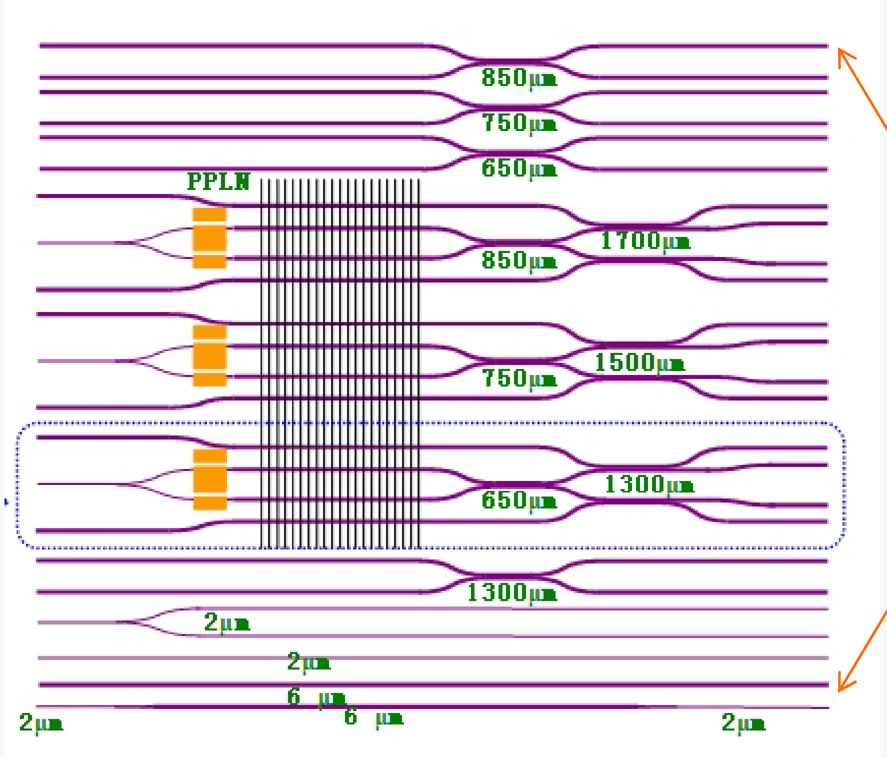


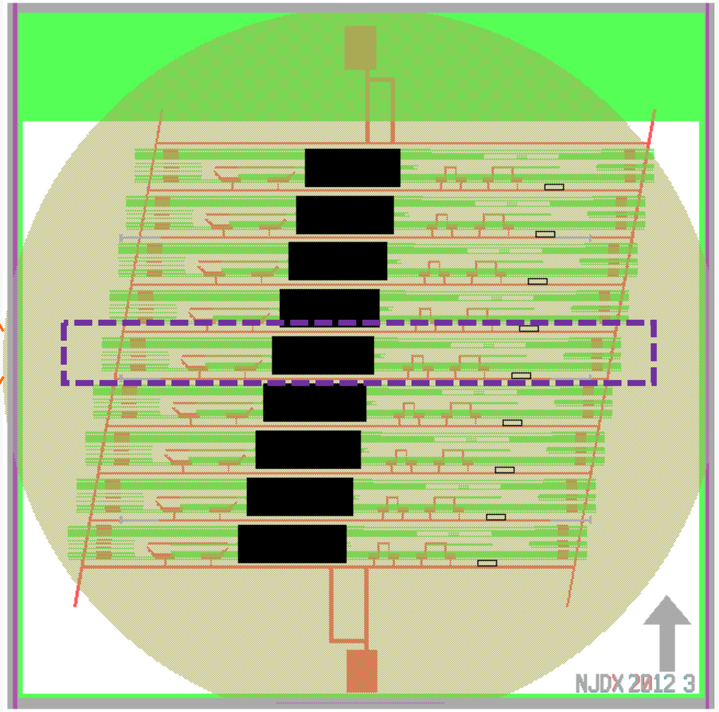
Input: classical pump laser



Output: Quantum light

Mask design: multi-channel, covering C-, L- band

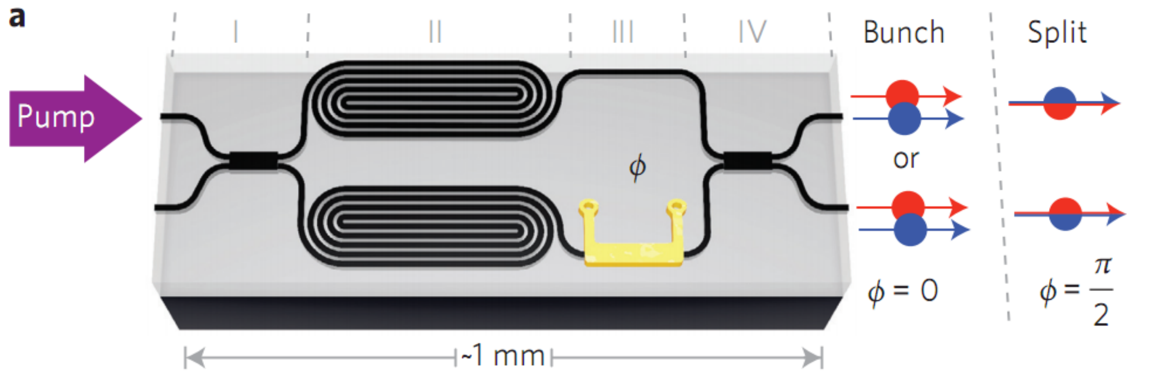




nature photonics
LETTERS
PUBLISHED ONLINE: 15 DECEMBER 2013 | DOI: 10.1038/NPHOTON.2013.339

On-chip quantum interference between silicon photon-pair sources

J. W. Silverstone[1], D. Bonneau[1], K.
C. M. Natarajan[3], M. G. Tanner[4], R
J. L. O'Brien[1] and M. G. Thompsor



LN V.S. SOI chip

	LN	SOI
Input power(mW)	**0.039**	**15**
Rep. rate	电光 ~ **40 GHz**	热 ~ **KHz**
Flux (Hz nm^{-1} mW^{-1})	**1.1×10^{7}**	**2.7×10^{3}**
Length (mm)	**10**	**5.2**

1. **低功耗**
2. **光子产生效率高三个量级;**
3. **光子调制效率高三个量级;**
4. **光子工作波长:**

… …

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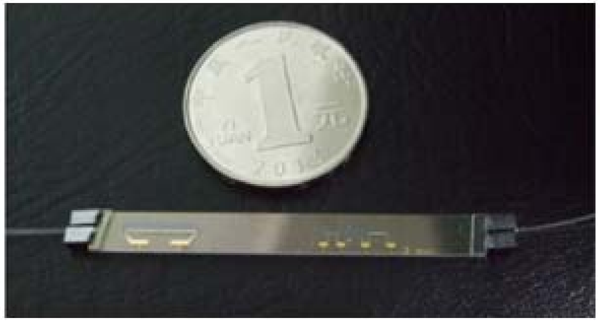


Synopsis: Quantum Photonics on a Chip

On a single chip, sources of entangled photons are combined with optical elements that can perform complex manipulations of quantum signals.

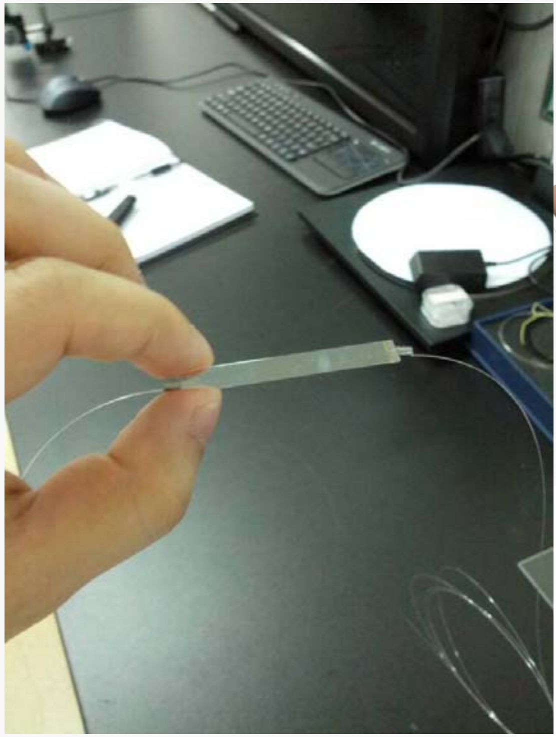
Featured in Physics | Editors' Suggestion

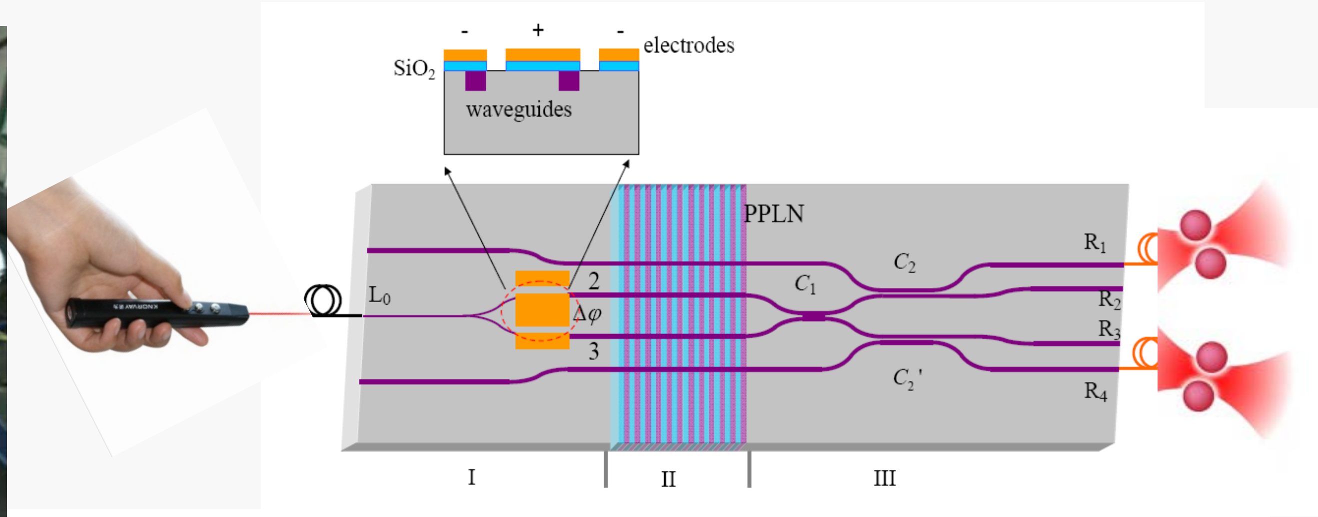
On-Chip Generation and Manipulation of Entangled Photons Based on Reconfigurable Lithium-Niobate Waveguide Circuits

H. Jin, F. M. Liu, P. Xu, J. L. Xia, M. L. Zhong, Y. Yuan, J. W. Zhou, Y. X. Gong, W. Wang, and S. N. Zhu

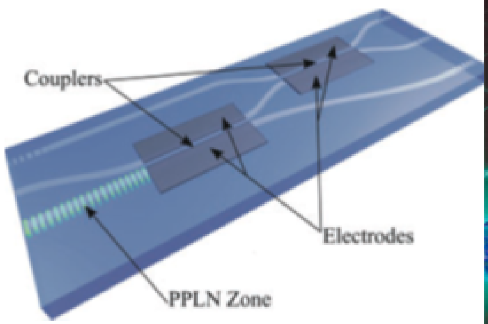
Phys. Rev. Lett. 113, 103601 (2014) – Published 4 September 2014

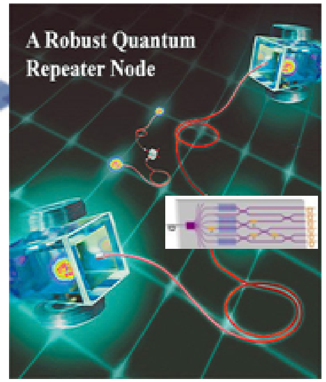
Quantum sources in the hands

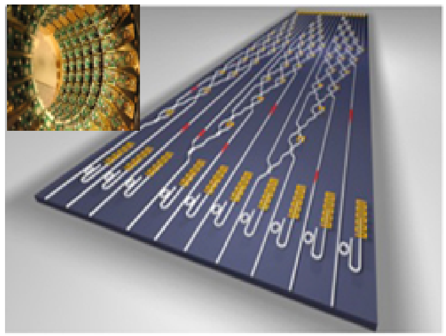




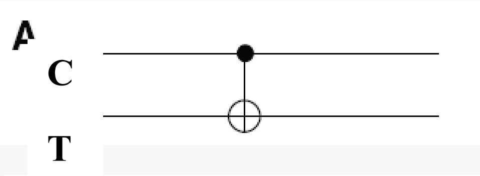
应用



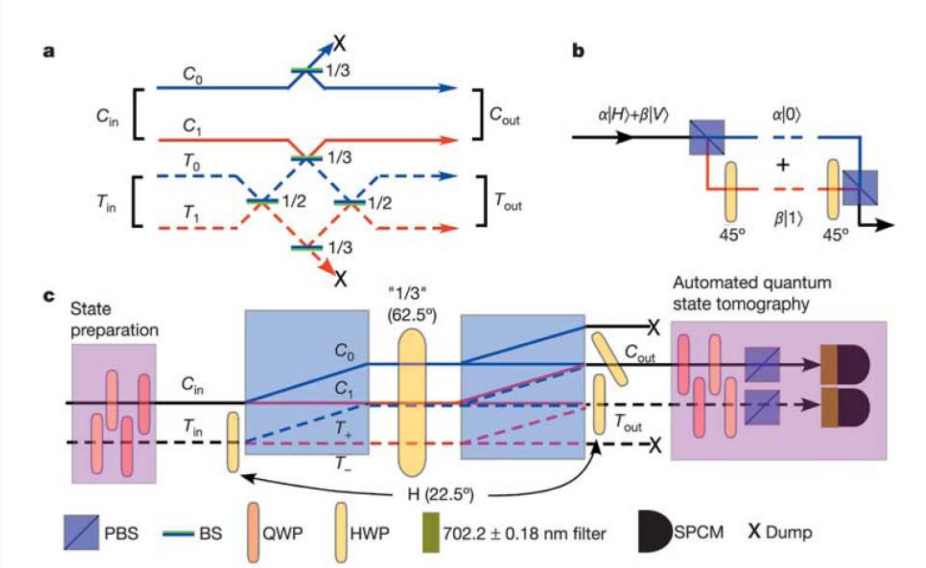




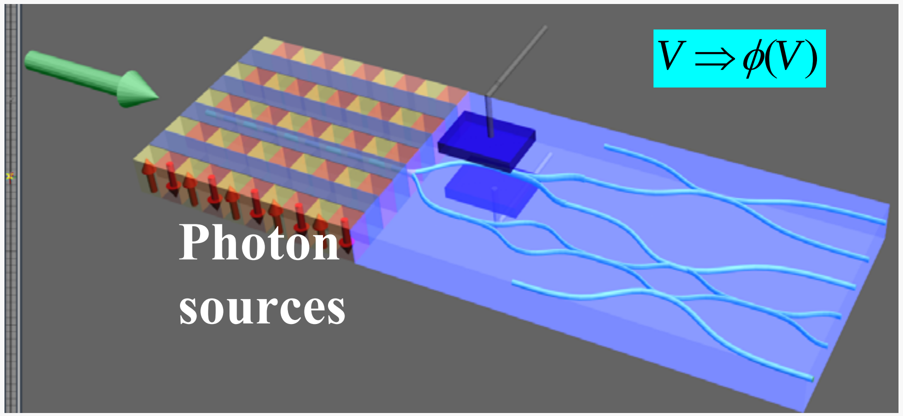
量子控制非门(C-NOT)

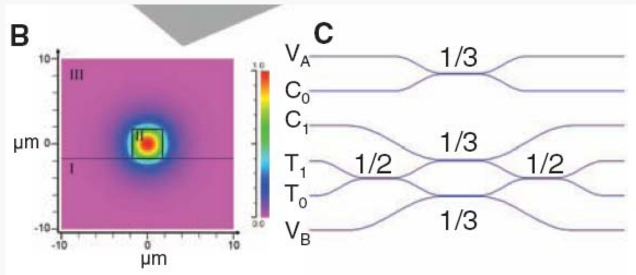


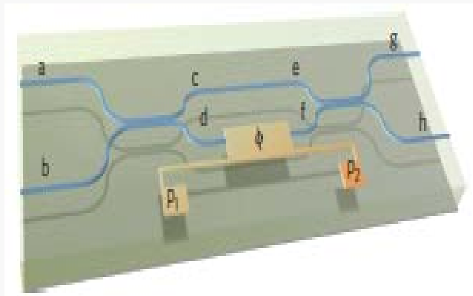
$$\mathcal{U}_{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}.$$



O’Brien *et al*. Nature 426(2003)



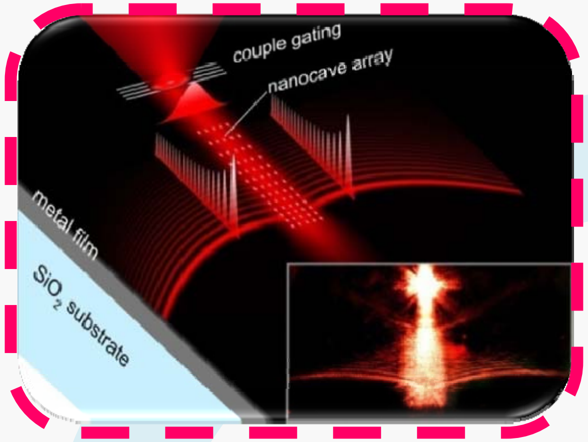




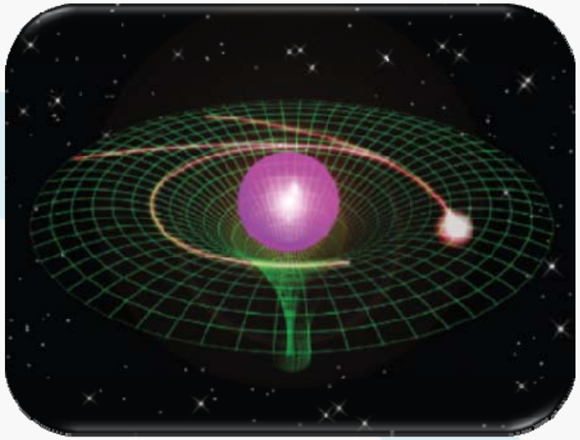
二种方案:LN晶片; 2.Si和PPLN晶片键合

O’Brien *et al*. Science, 646(2008)

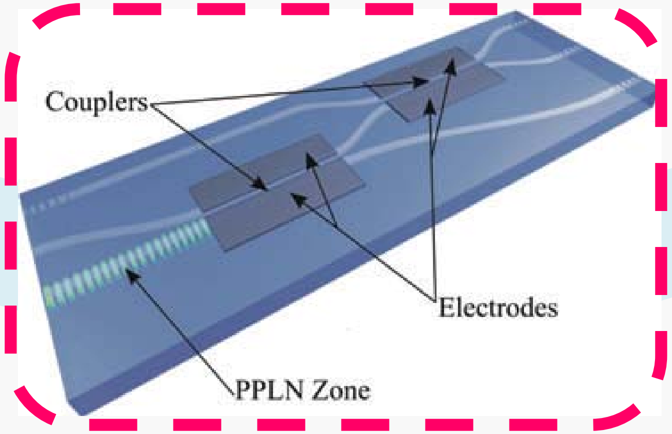
SPP 光子集成及量子芯片



光学模拟芯片

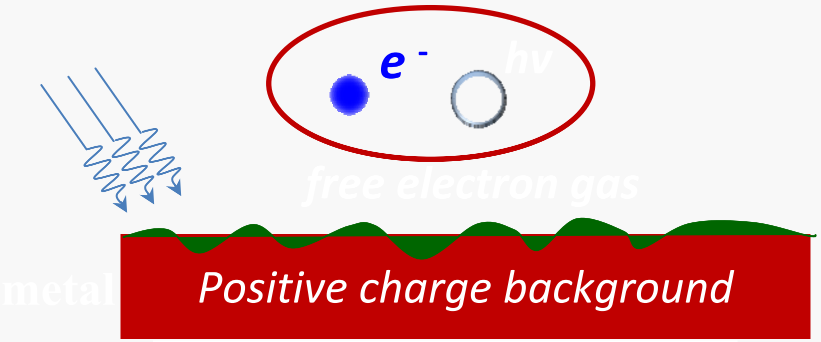


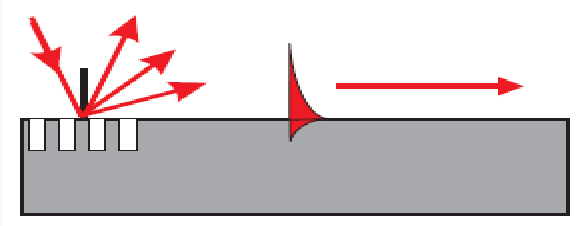
On Chip Photonics & Optoelectronics



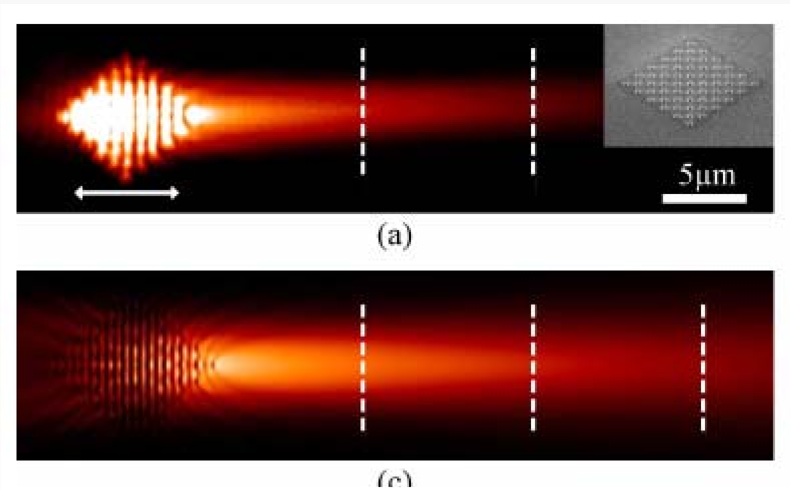
LN 集成量子芯片

表面等离激元(SPP)的传播调控: I. 耦合与传输

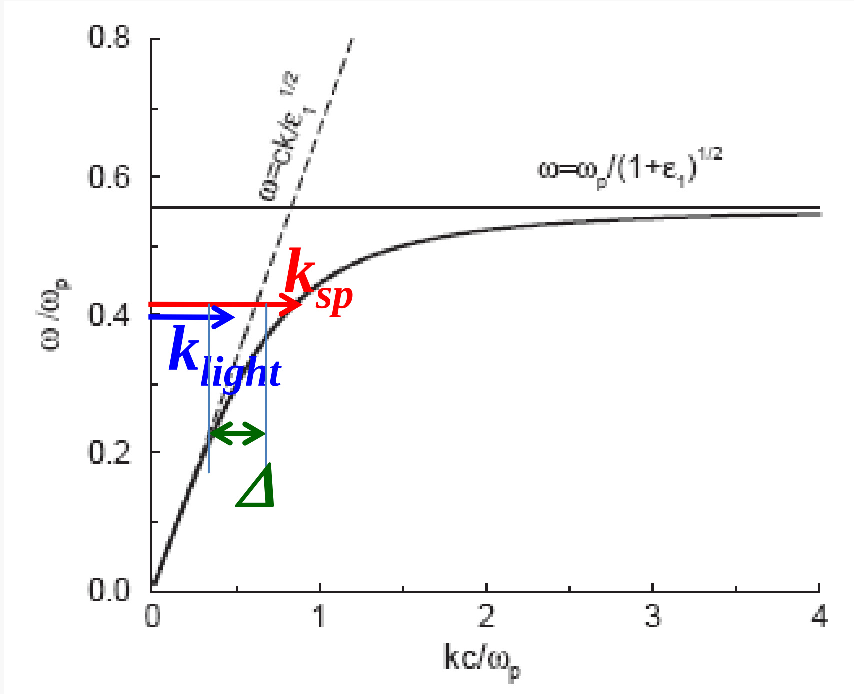




光栅耦合



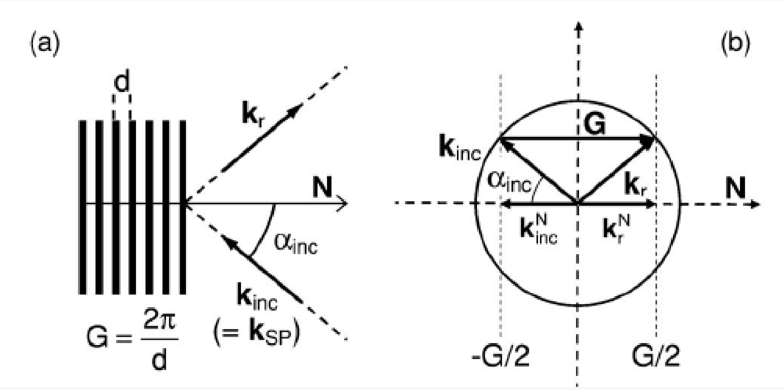
Collimate beam, OE 15, 3488 (2007)

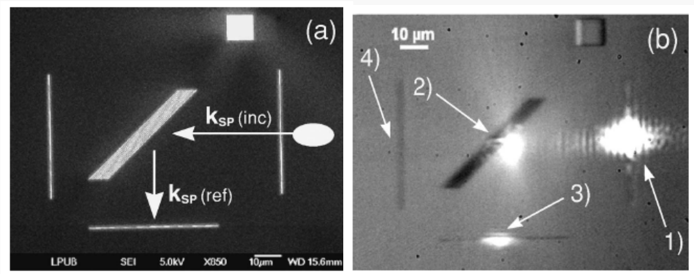


$$\Delta \varpi = 0$$

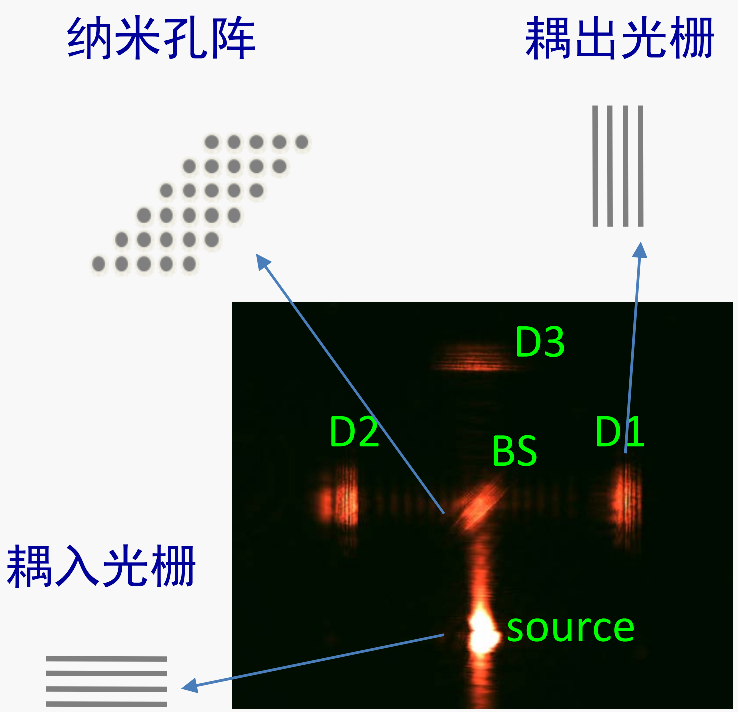
$$\Delta k = 0.$$

表面等离激元(SPP)的传播调控: II. 反射与分束





SPP Bragg mirror,
PRB 73, 155416 (2006)



Bragg 光栅作为SPP反射镜 → Bragg 点阵作为SPP分束器

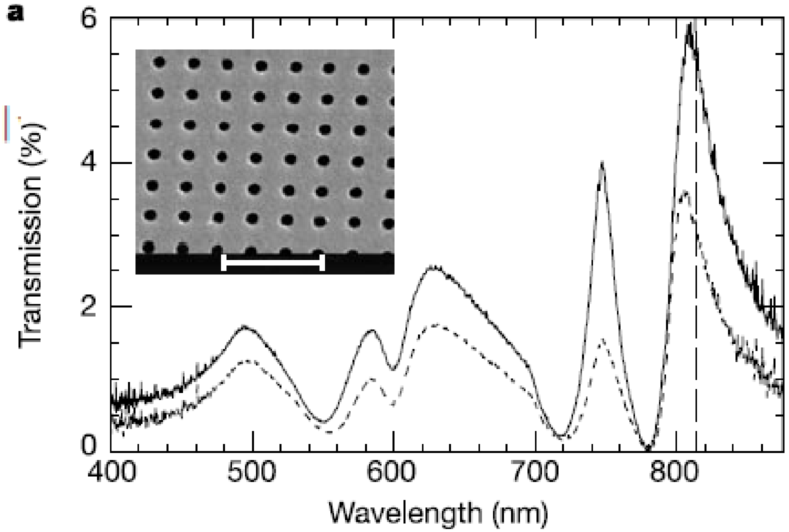
letters to nature

NATURE | VOL 418 | 18 JULY 2002 |

Plasmon-assisted transmission of entangled photons

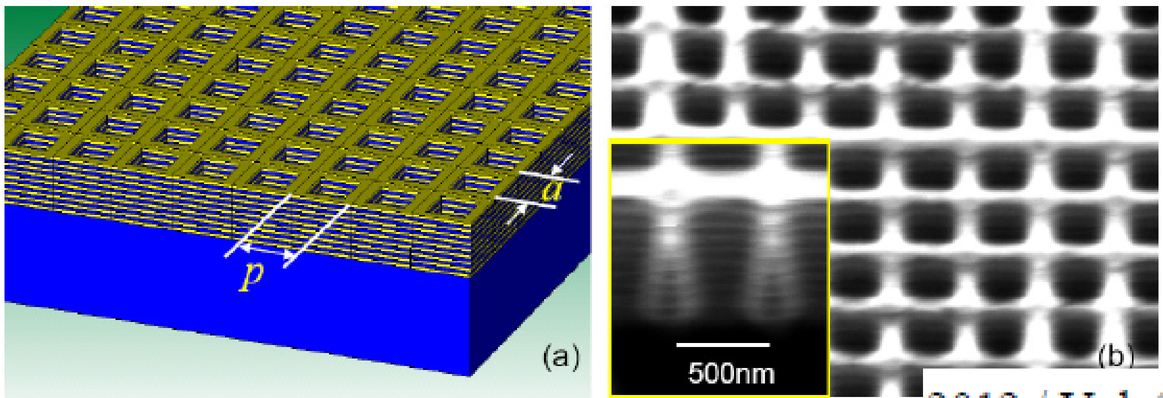
E. Altewischer, M. P. van Exter & J. P. Woerdman

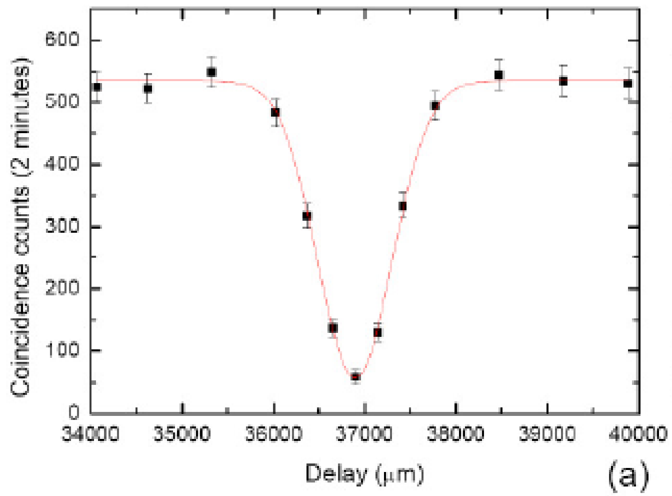
Leiden University, Huygens Laboratory, PO Box 9504, 2300 RA Leiden, The Netherlands



Hong-Ou-Mandel interference mediated by the magnetic plasmon waves in a three-dimensional optical metamaterial

S. M. Wang,[1,3] S. Y. Mu,[1] C. Zhu,[1] Y. X. Gong,[1] P. Xu,[1] H. Liu,[1,*] T. Li,[1] S. N. Zhu,[1] and X. Zhang[2]

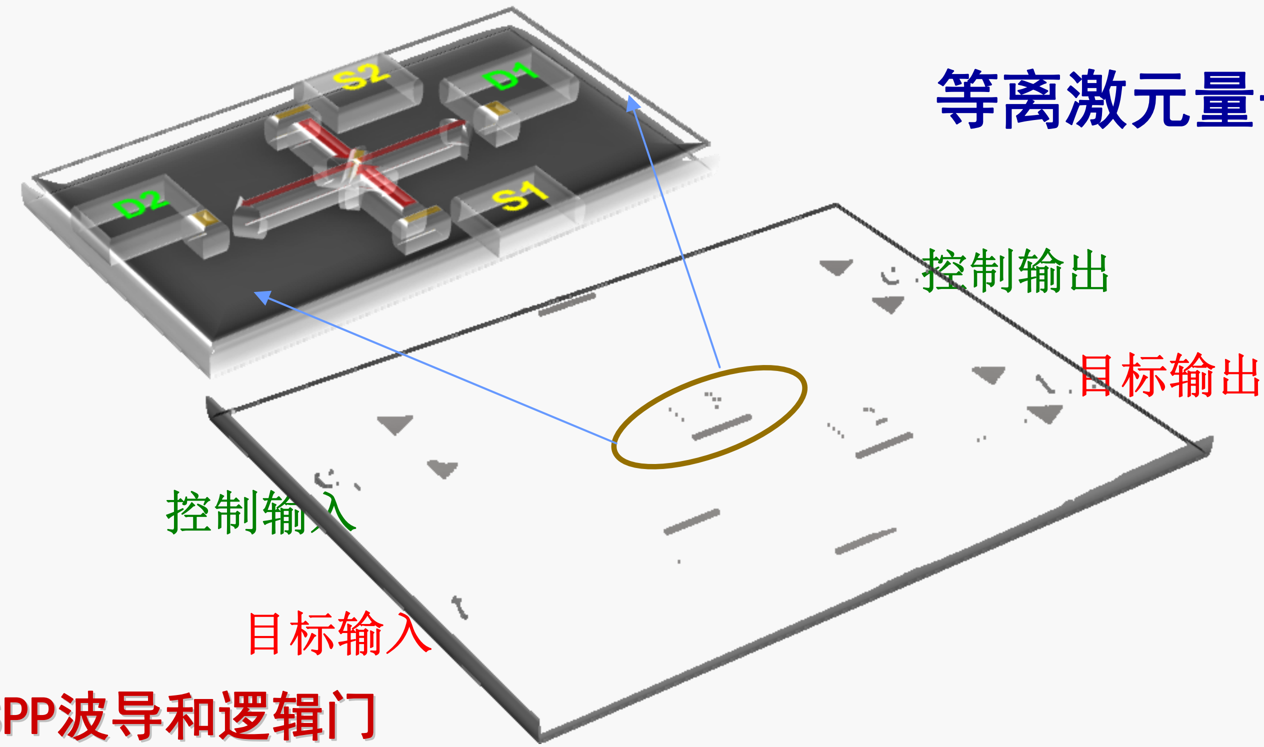




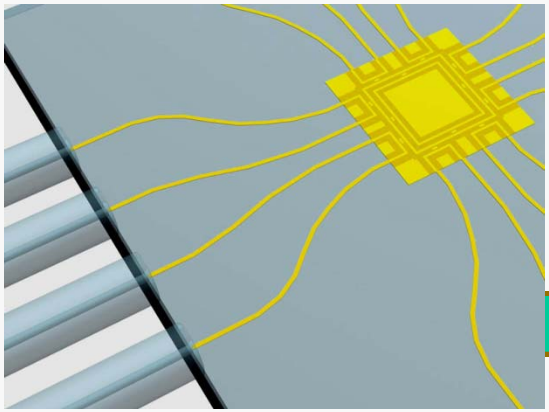
2012 / Vol. 20, No. 5 / OPTICS EXPRESS 5213

基于SPP和MPP(超构材料)的量子集成光路

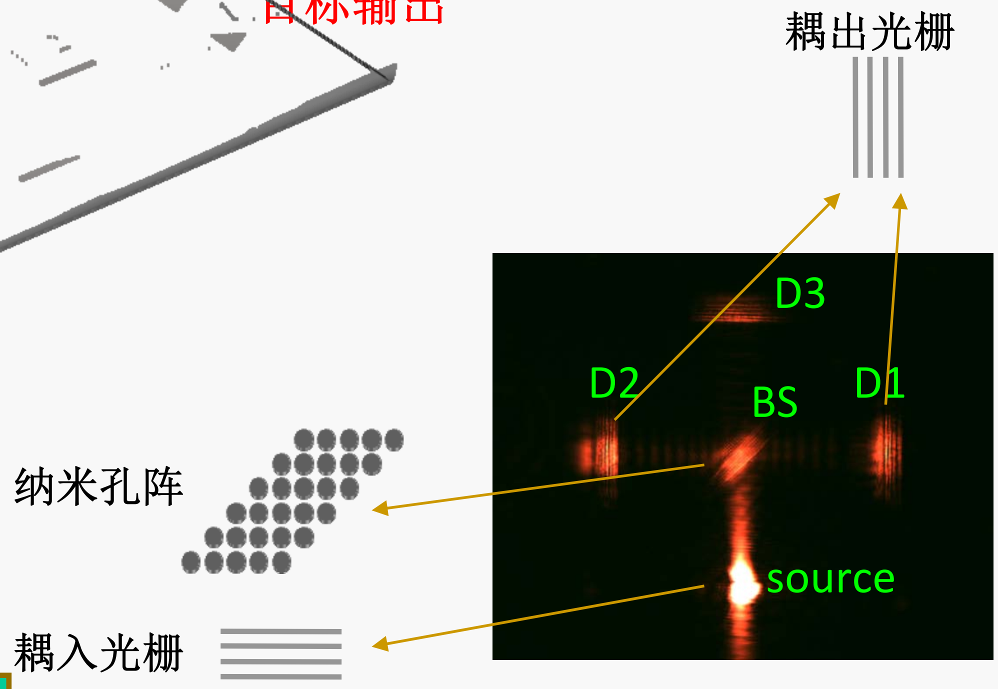
等离激元量子CNOT门器件



SPP波导和逻辑门

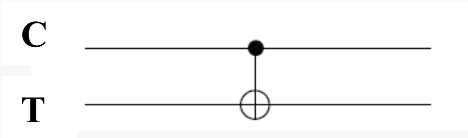


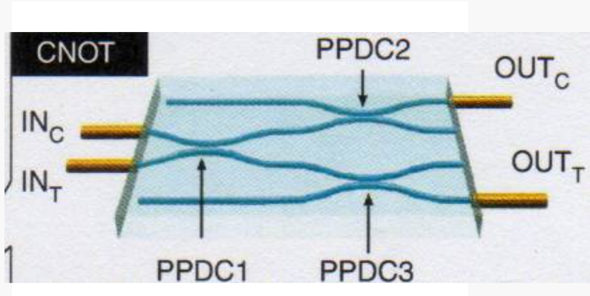
元件尺寸**2~5um**

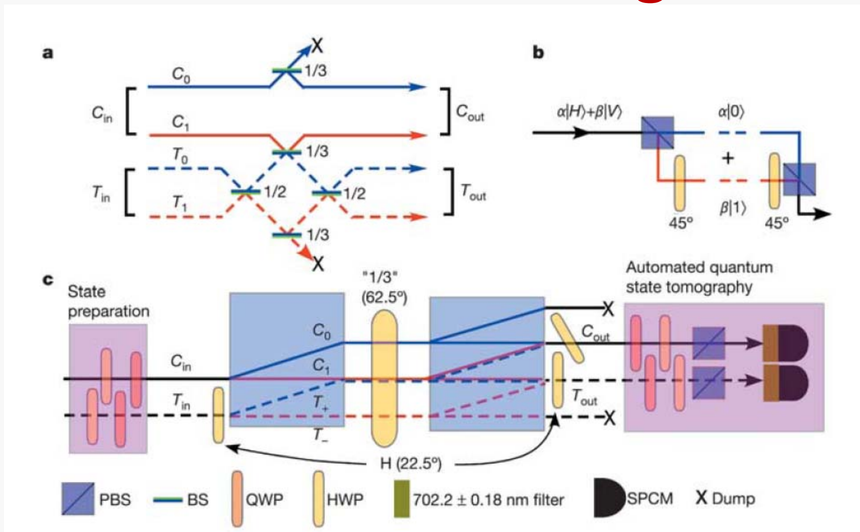


初步的**SPP**分束实验

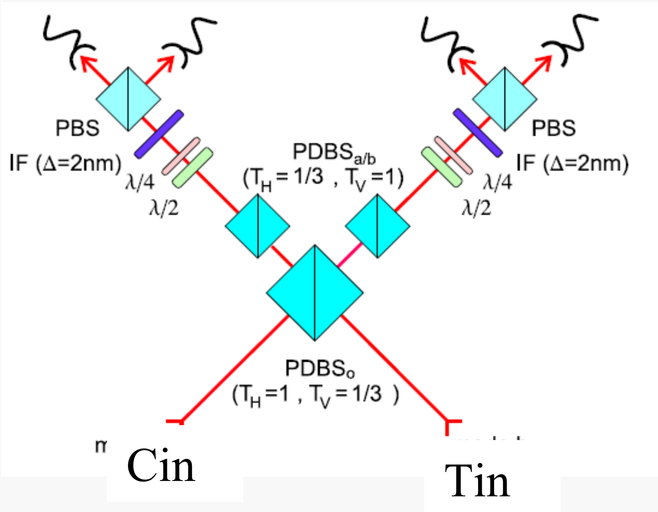
表面等离激元(SPP)的传播调控：III. Q-CNOT gate



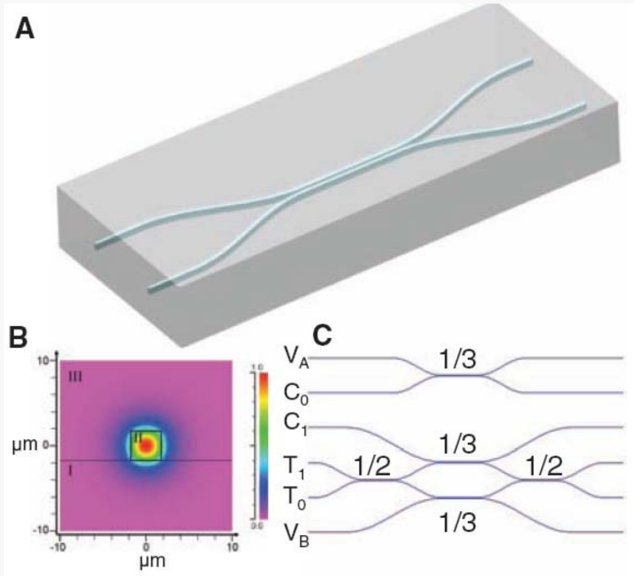




O'Brien *et al*. Nature 426(2003)



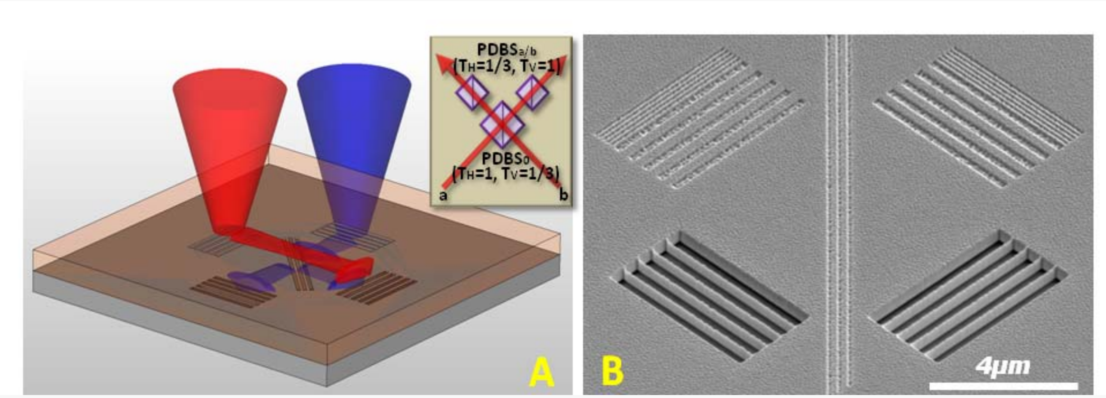
Nikolai *et al*., PRL 95,210505(2005)

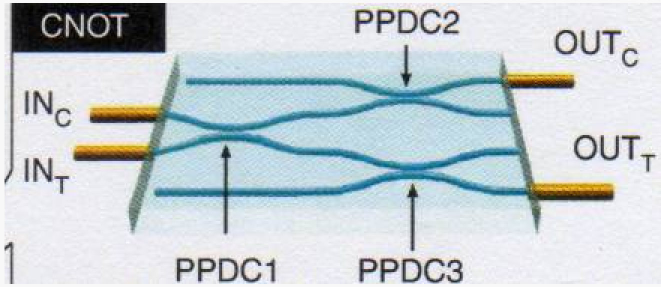


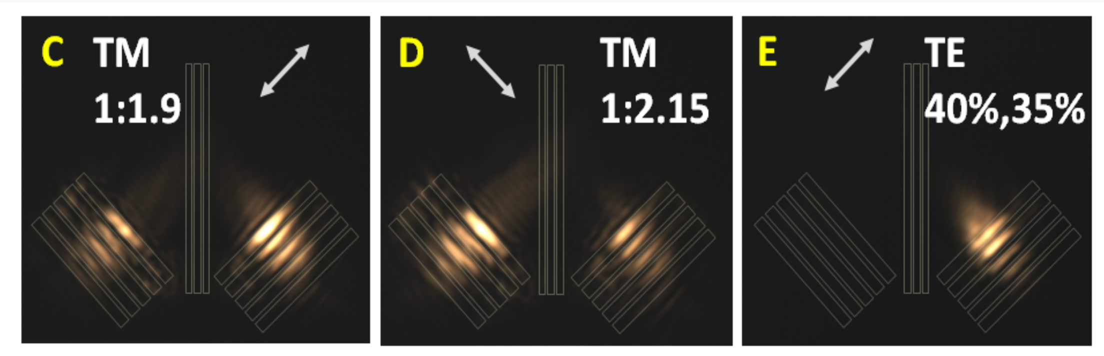
O'Brien *et al*. Science, 646(2008)

表面等离激元(SPP)的传播调控：III. Q-CNOT gate

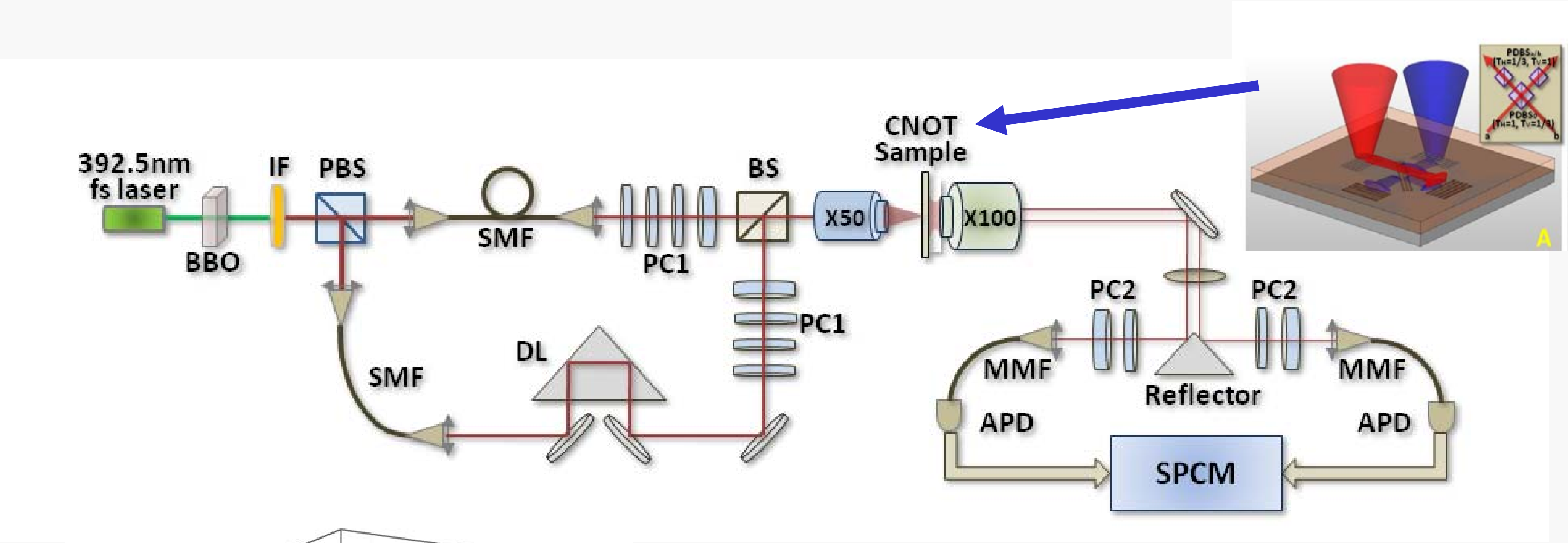
介质加载SPP波导体系中TM、TE的特殊分束 → **量子CNOT门**

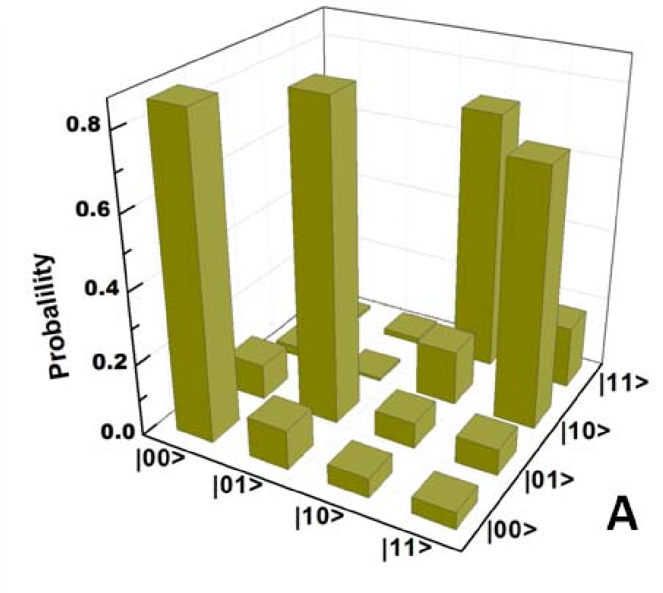






表面等离激元(SPP)的传播调控：III. Q-CNOT gate





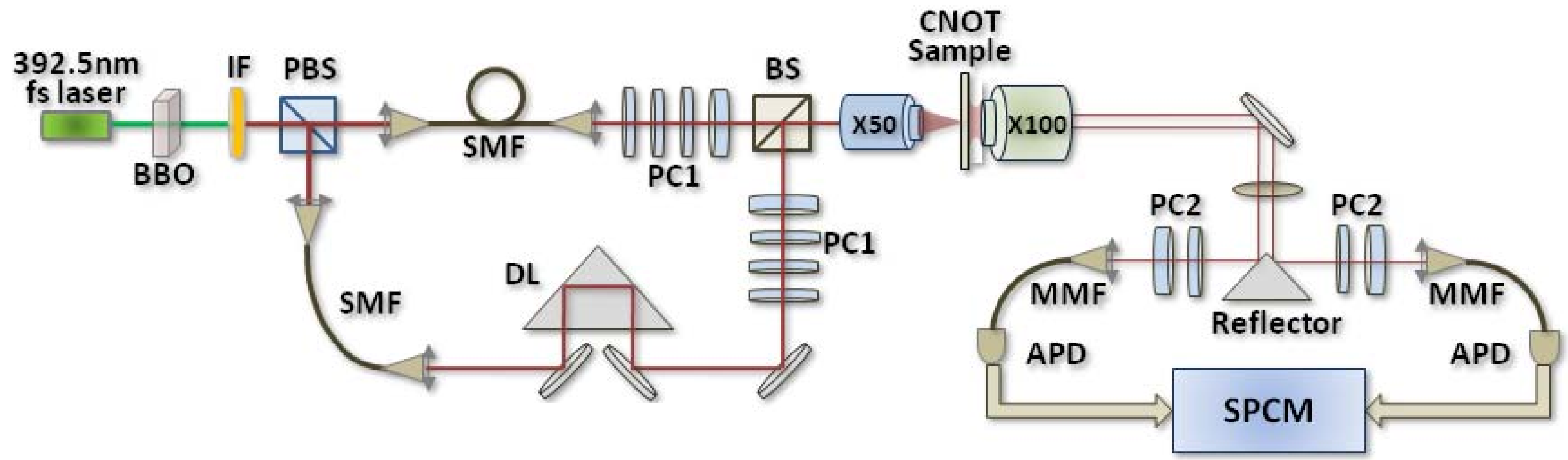
$$|0\rangle_c \equiv |TE\rangle_c$$

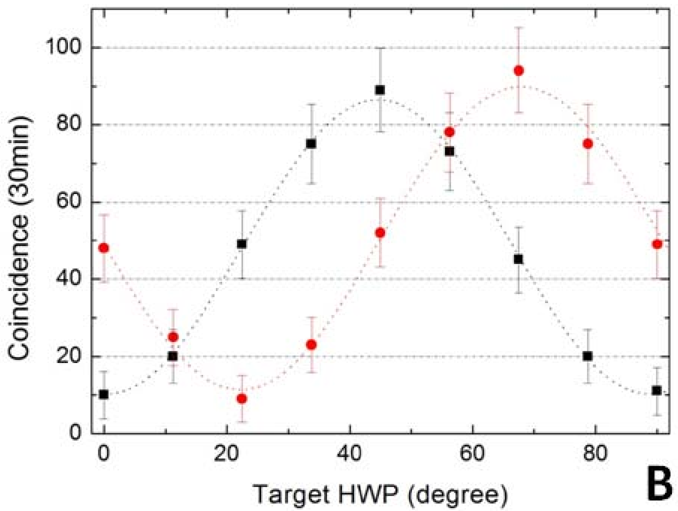
$$|1\rangle_c \equiv |TM\rangle_c$$

$$|0\rangle_t \equiv |D\rangle_t = \left(|TE\rangle_t + |TM\rangle_t\right)/\sqrt{2}$$

$$|1\rangle_t \equiv |A\rangle_t = \left(|TE\rangle_t - |TM\rangle_t\right)/\sqrt{2}$$

表面等离激元(SPP)的传播调控：III. Q-CNOT gate





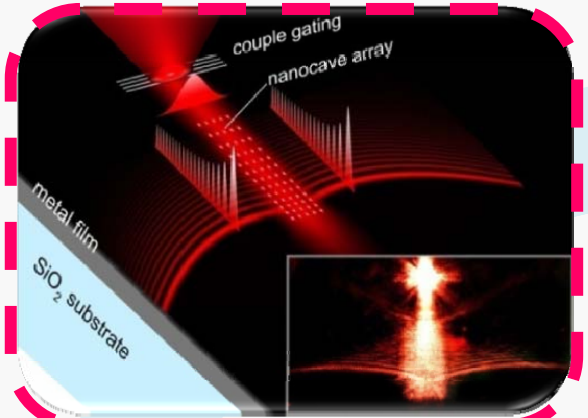
violate Bell inequalities

Input: $(|0\rangle_c - |1\rangle_c)|1\rangle_t/\sqrt{2}$

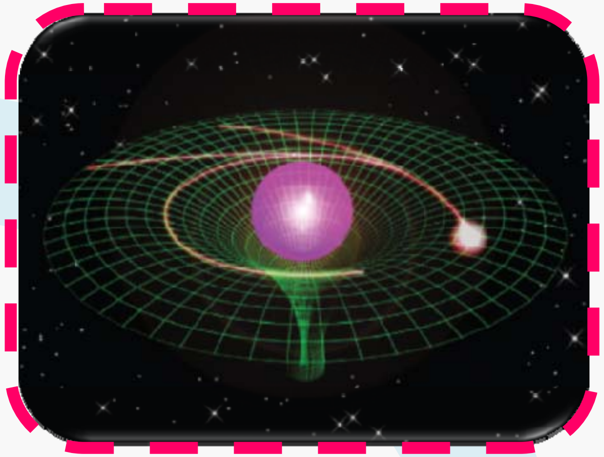
Ouput: $|0\rangle_c \ \& \ (|0\rangle_c + |1\rangle_c)/\sqrt{2}$

Bell State $|\psi^-\rangle = (|01\rangle - |10\rangle)/\sqrt{2}$

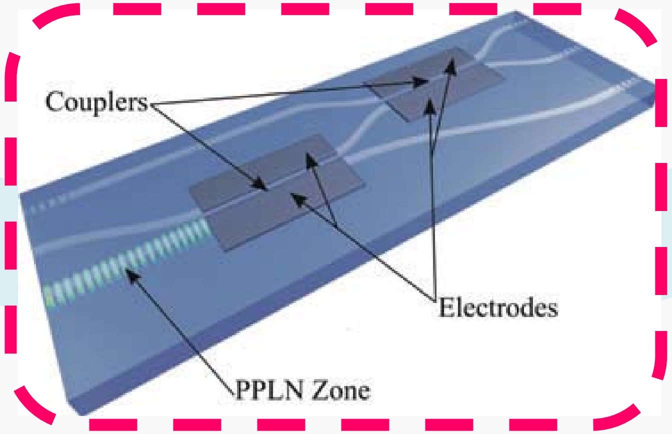
SPP 光子集成及量子芯片



光学模拟芯片



On Chip Photonics & Optoelectronics

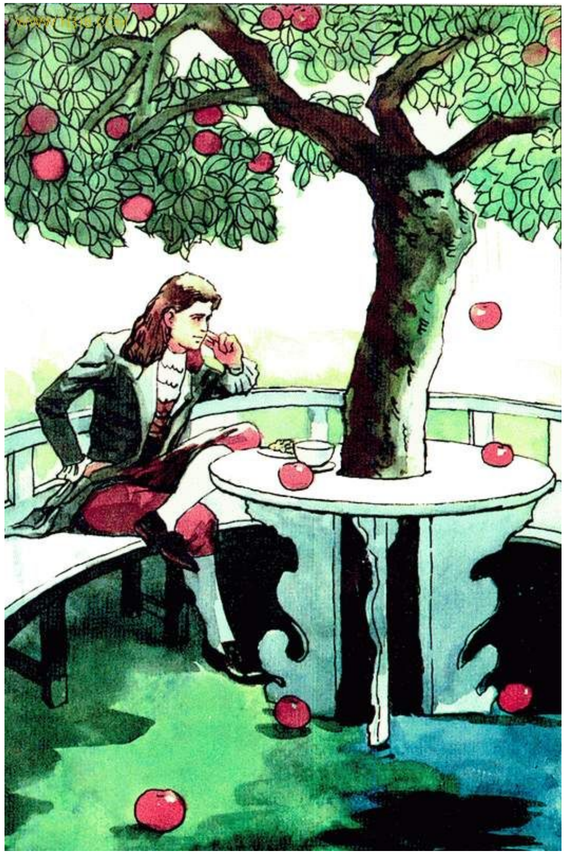


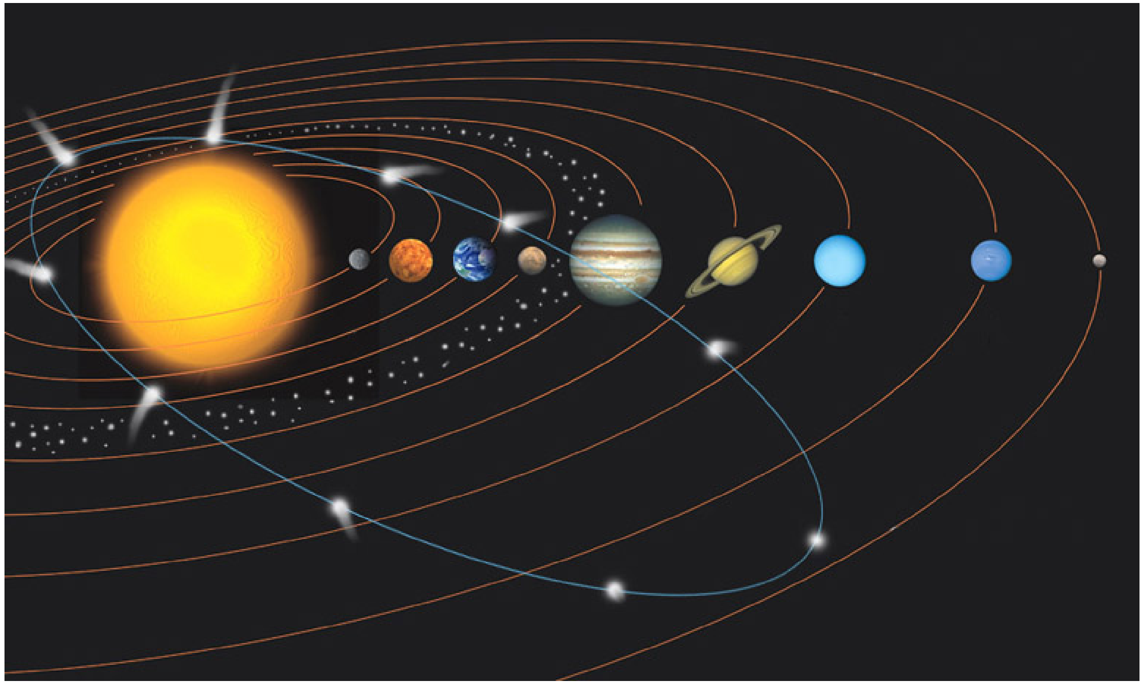
LN 集成量子芯片

牛顿的平直时空观（欧几里德空间、笛卡尔坐标）

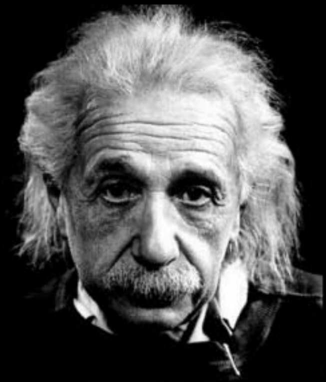
$$F = G\frac{mM}{r^2}$$

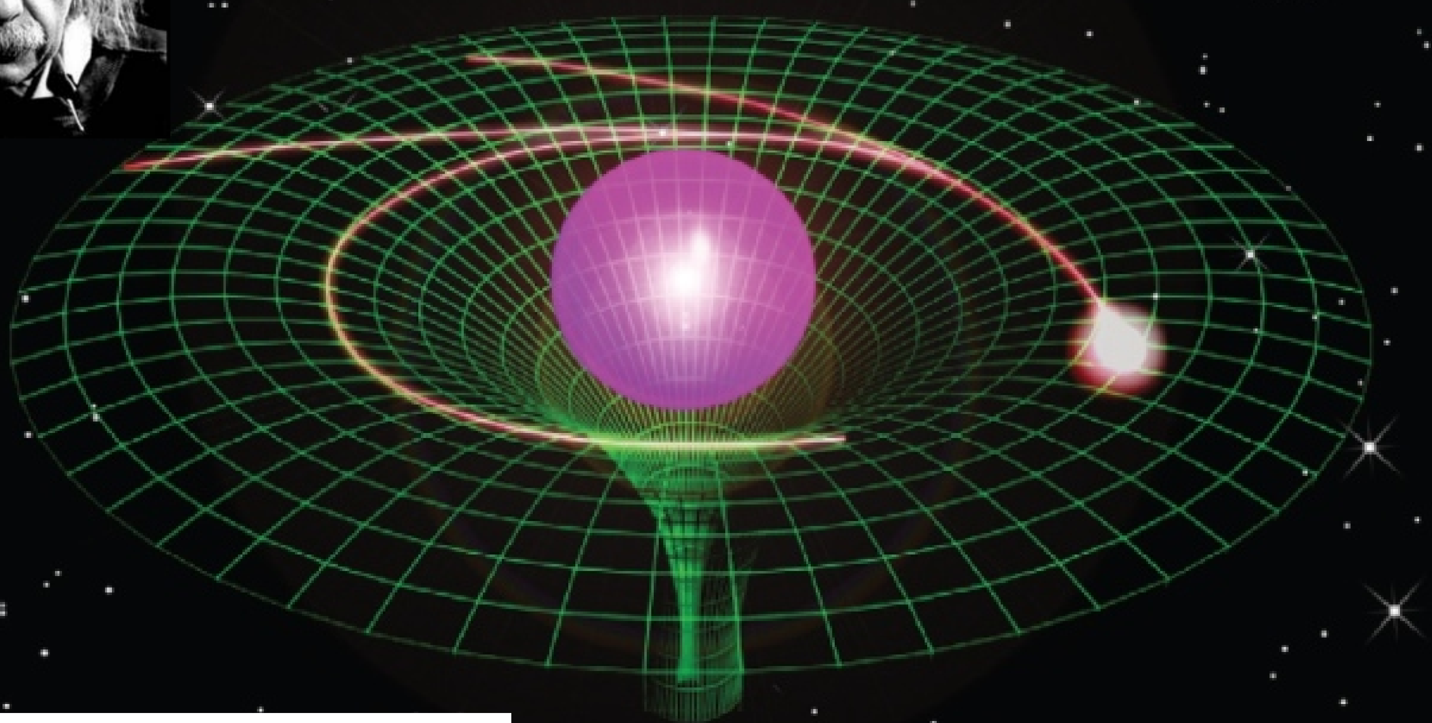
$$r^2 = x^2 + y^2 + z^2$$





广义相对论与时空弯曲

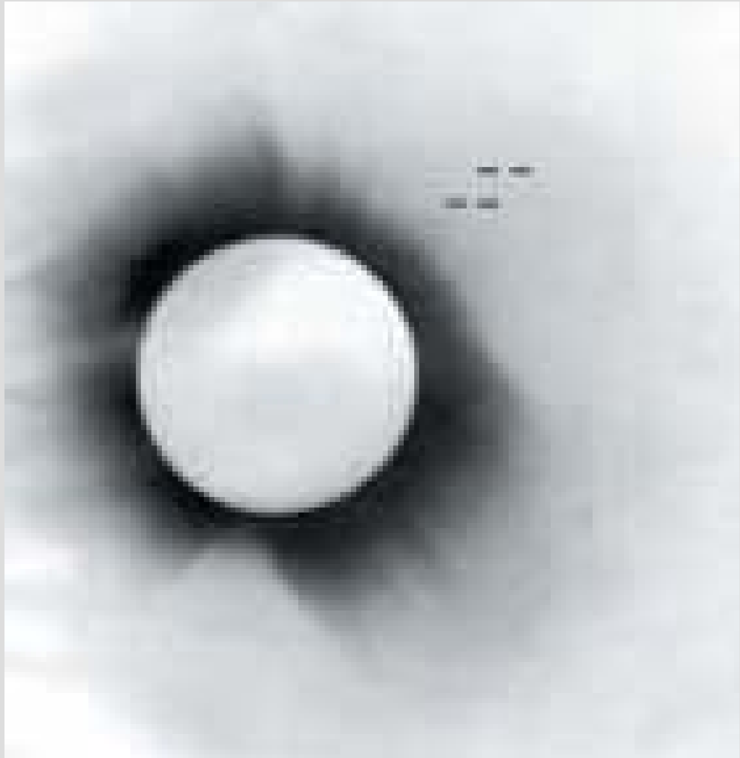




$$G_{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

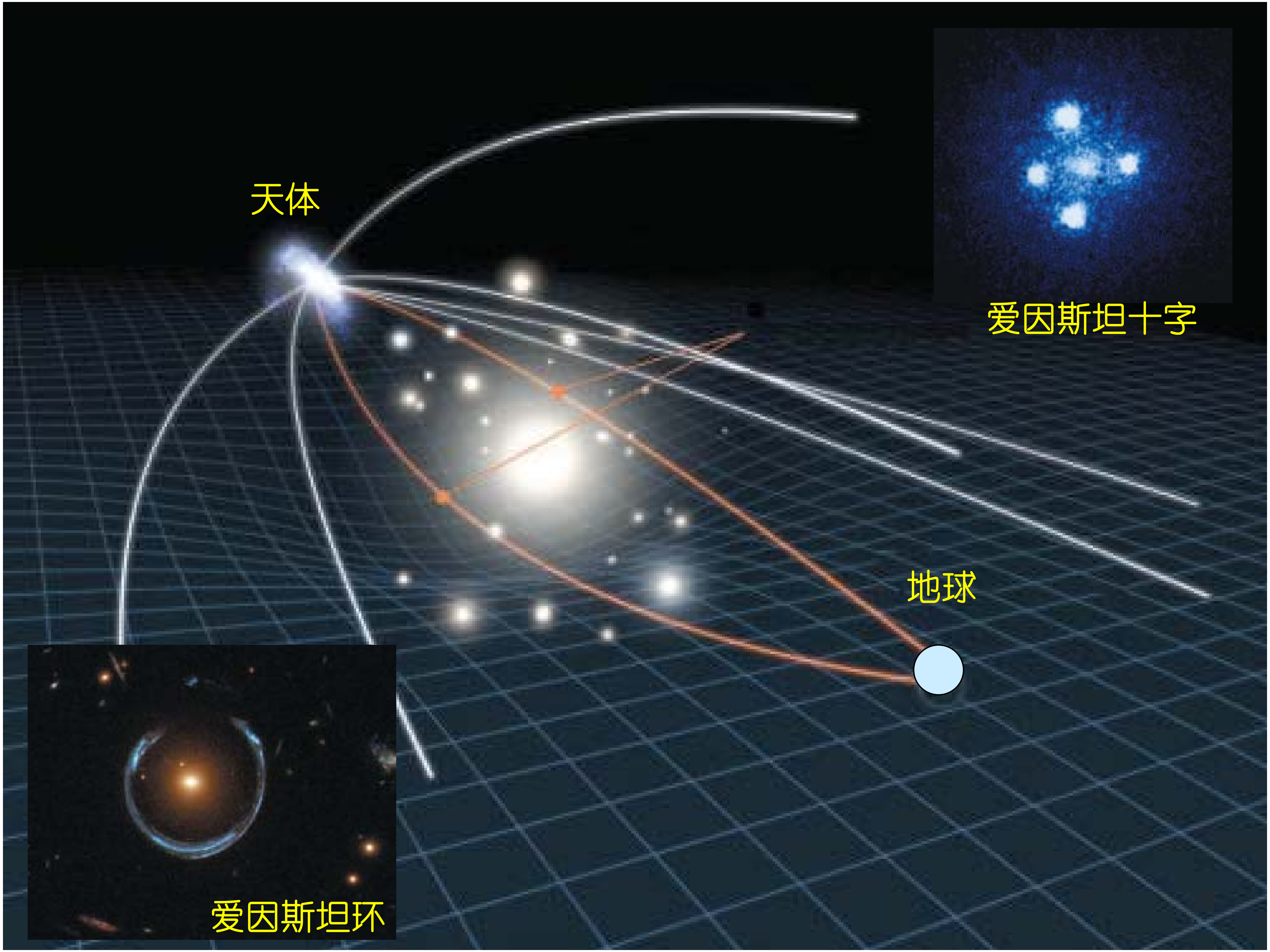
$$ds^2 = \left(1 - \frac{2GM}{r}\right) dt^2 - \frac{dr^2}{1 - \frac{2GM}{r}} - r^2 d\theta^2 - r^2 \sin^{2\vartheta} d\theta$$

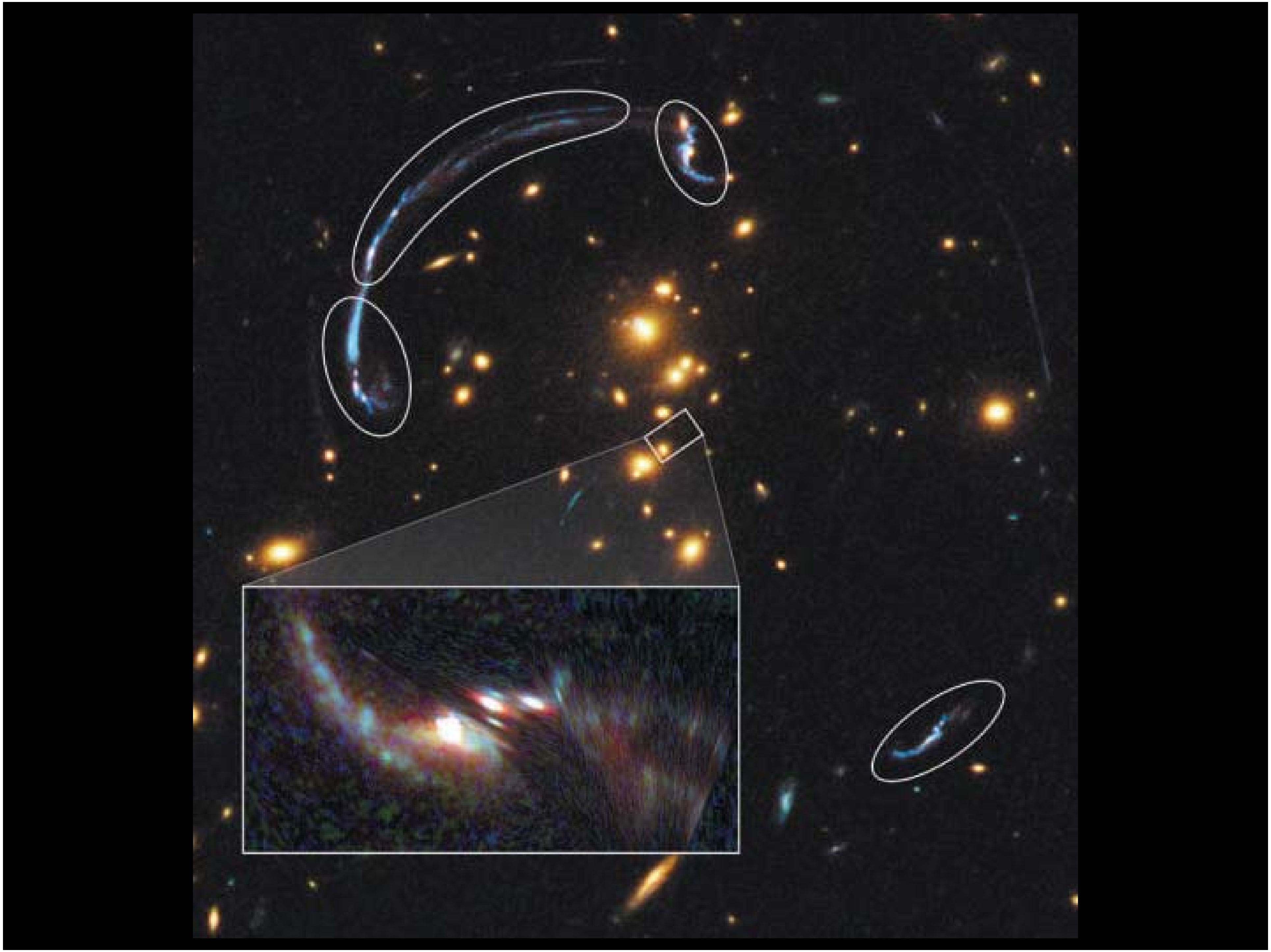
广义相对论与时空弯曲的实验验证



爱丁顿爵士率领的远征队在1919 年日全食时拍摄的负片。
证实了爱因斯坦关于太阳会偏折从附近经过的星光的预言。

“I am wondering who the third one is?”


天体
爱因斯坦十字
地球
爱因斯坦环



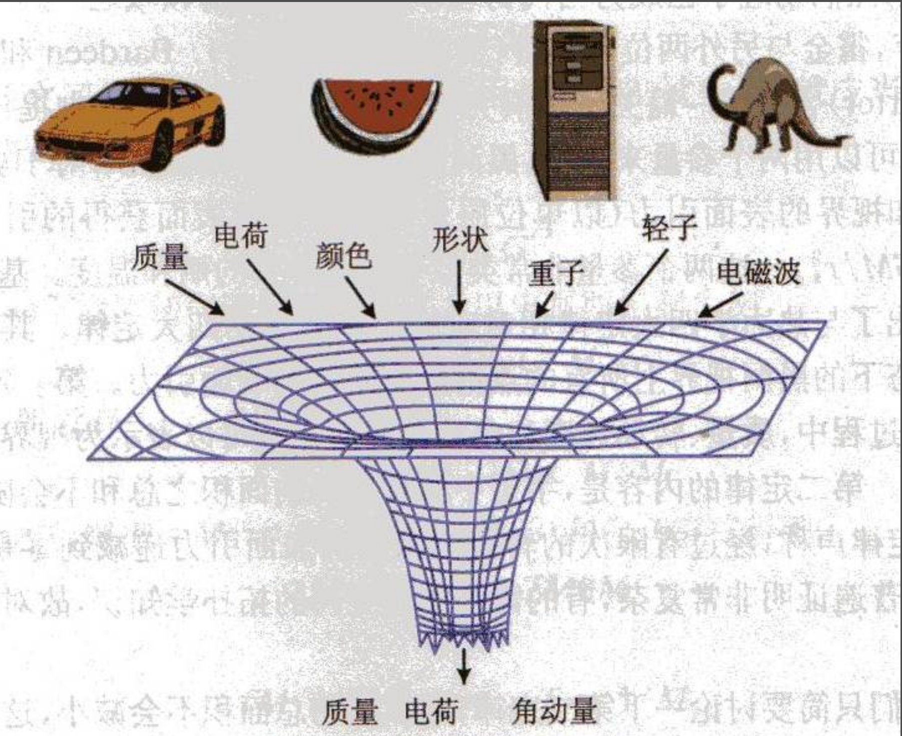


图 4.10 黑洞的"三毛定理"

白矮星 < 1.4 M⊙

中子星

黑　洞 > 3.2 M⊙

$$\upsilon^2 = \frac{2GM}{R}$$

$$r_s \equiv \frac{2GM}{c^2}$$

史瓦西半径

视　　　界

表 4.1　典型天体的密度与表面引力场强度

天体名称	平均密度(g/cm^3)	引力强度参数($2GM/Rc^2$)
地球	5	10^{-9}
太阳	1	10^{-6}
白矮星	$\sim 10^6$	$\sim 10^{-4}$
中子星	$\sim 10^{14}$	$\sim 10^{-1}$
黑洞		1

引力透镜效应

- 根据广义相对论，光子可以被天体周围的引力场所捕获
- 能否模拟引力透镜效应，设计和制备一种新型的微腔来捕获光子

介质折射率模拟引力场

引力场方程: $G_{\mu\nu} = -T_{\mu\nu} = -\rho u_\mu u_\nu - p(u_\mu u_\nu - g_{\mu\nu})$

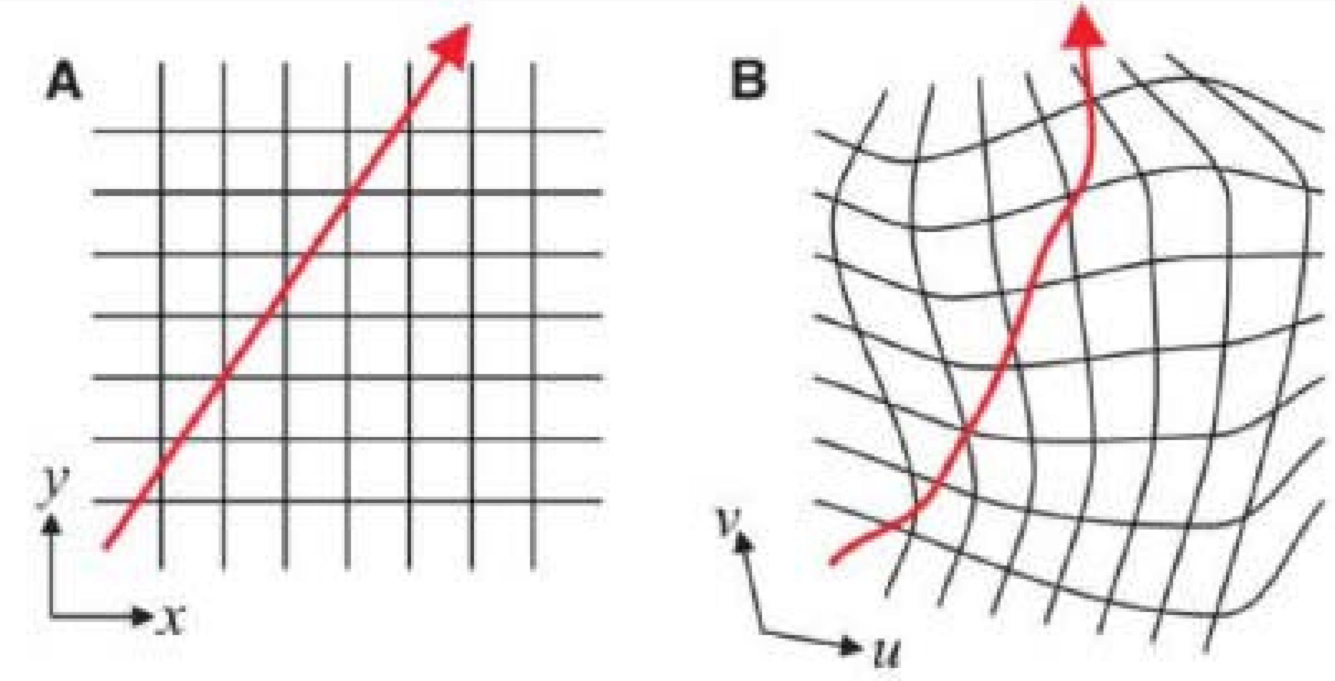
$$ds^2 = e^{2\nu} c^2 dt^2 - e^{2\lambda}(dr^2 + r^2 d\Omega)$$

波动方程:
$$\begin{cases} \nabla \times \mathbf{E} = -\mu(\mathbf{r}) \cdot \dfrac{\partial \mathbf{H}}{\partial t} \\ \nabla \times \mathbf{H} = \varepsilon(\mathbf{r}) \cdot \dfrac{\partial \mathbf{E}}{\partial t} \end{cases}$$

$$\Rightarrow \nabla^2 U - \frac{n(\mathbf{r})^2}{c^2} \cdot \frac{\partial^2 U}{\partial t^2} = 0$$

我们能否通过控制介质的折射率模拟引力场？

材料中的变换光学



$$\varepsilon_u' = \varepsilon_u \frac{Q_u Q_v Q_w}{Q_u^{\,2}}$$

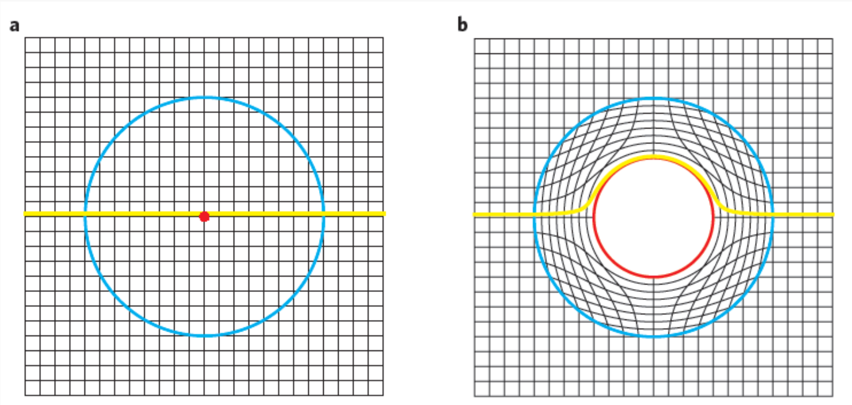
$$\mu_u' = \mu_u \frac{Q_u Q_v Q_w}{Q_u^{\,2}}$$

$$Q_u^2 = \left(\frac{\partial x}{\partial u}\right)^2 + \left(\frac{\partial y}{\partial u}\right)^2 + \left(\frac{\partial z}{\partial u}\right)^2$$

$$Q_v^2 = \left(\frac{\partial x}{\partial v}\right)^2 + \left(\frac{\partial y}{\partial v}\right)^2 + \left(\frac{\partial z}{\partial v}\right)^2$$

$$Q_w^2 = \left(\frac{\partial x}{\partial w}\right)^2 + \left(\frac{\partial y}{\partial w}\right)^2 + \left(\frac{\partial z}{\partial w}\right)^2$$

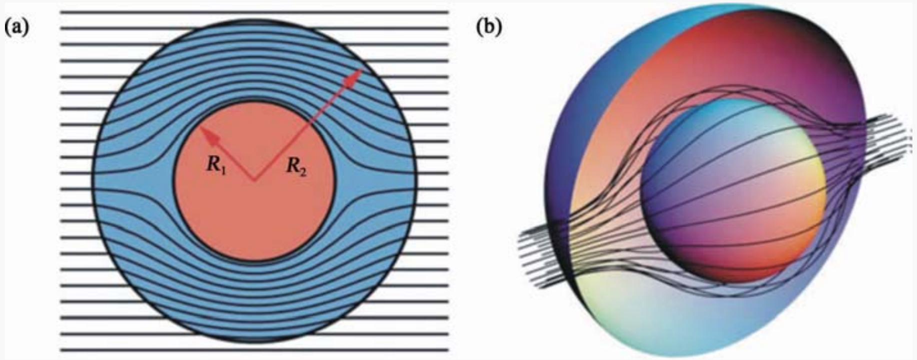
超构材料中的变换光学

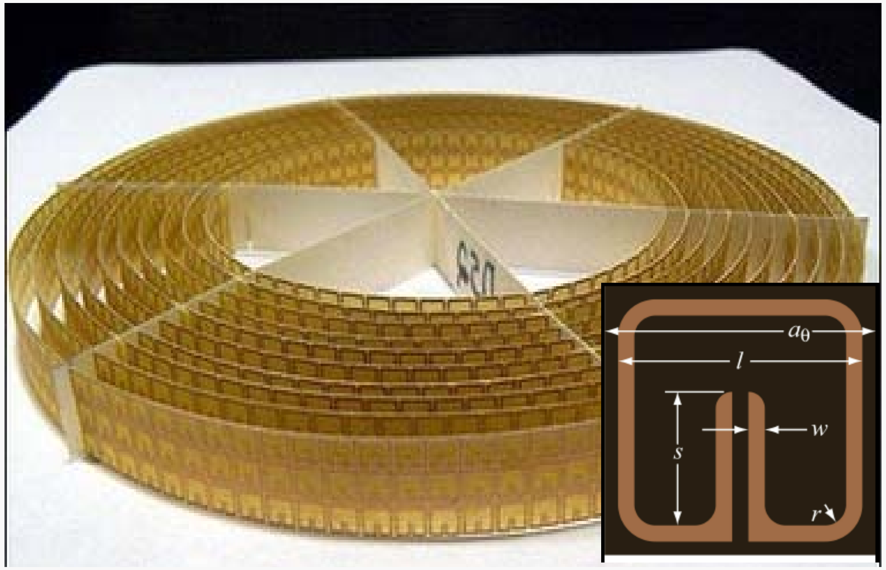


$$\varepsilon'_{r'} = \mu'_{r'} = \frac{R_2}{R_2 - R_1}\frac{(r' - R_1)^2}{r'},$$

$$\varepsilon'_{\theta'} = \mu'_{\theta'} = \frac{R_2}{R_2 - R_1},$$

$$\varepsilon'_{\phi'} = \mu'_{\phi'} = \frac{R_2}{R_2 - R_1}$$

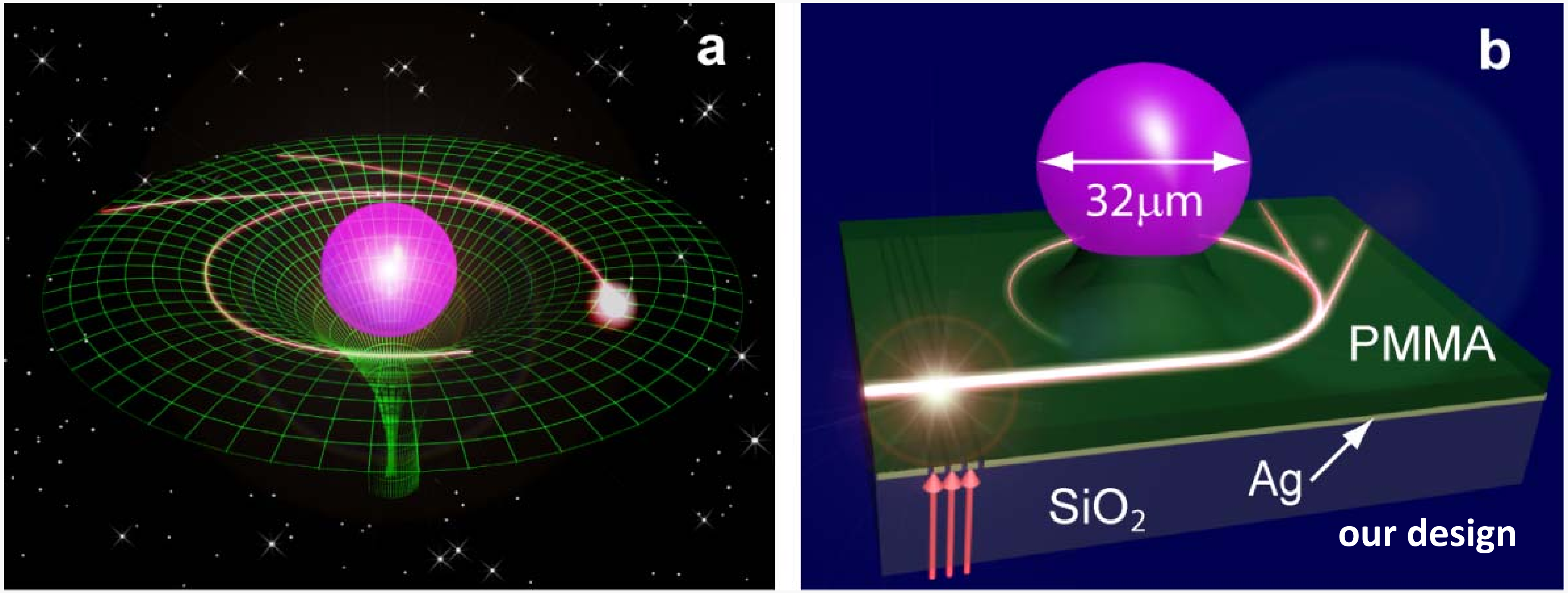




J. B. Pendry et al.,Science **312**, 1780

U. Leonhardt, Science **312**, 1777

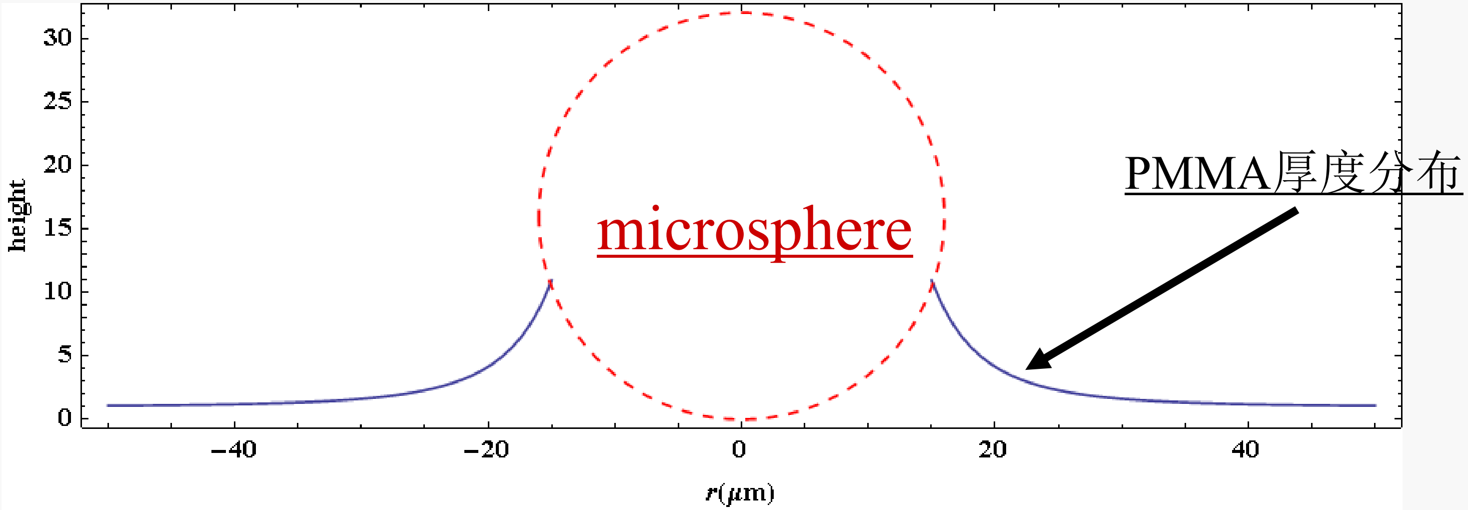
芯片的设计



制备工艺：旋涂

天体 = 微球；　　引力场 = 弯曲波导

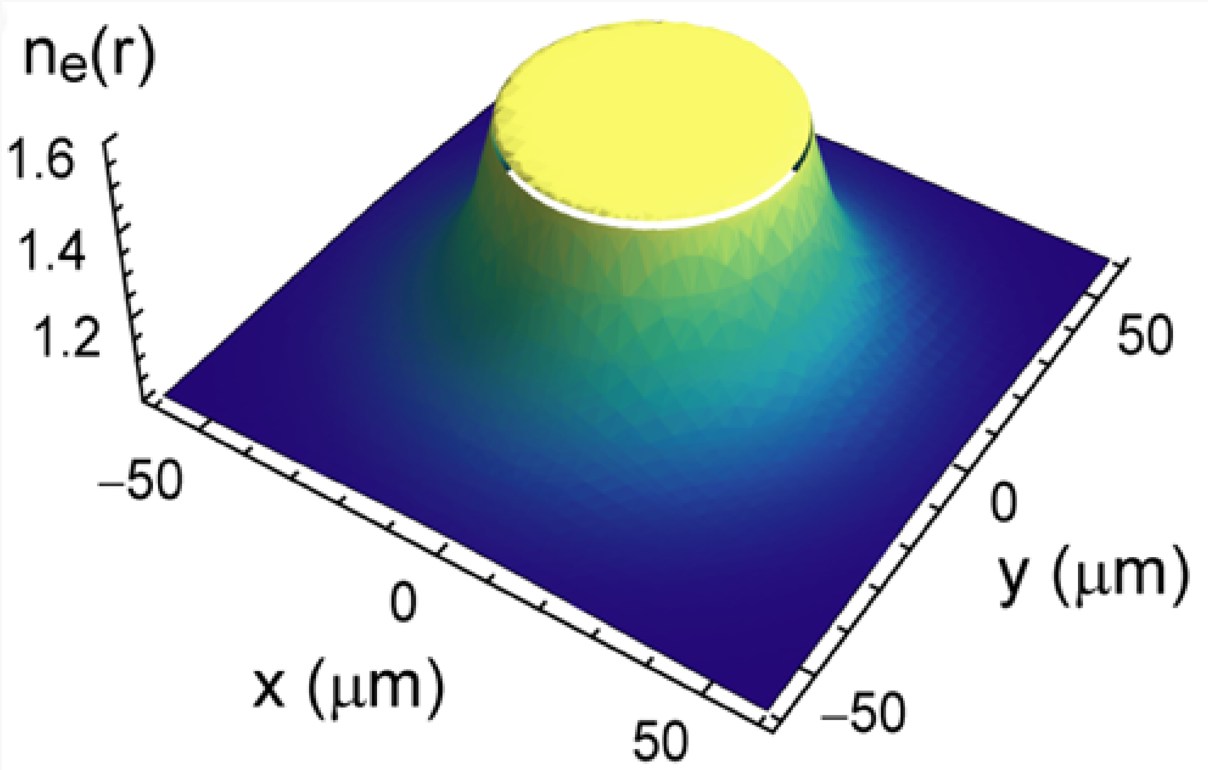
微球附近PMMA厚度分布



这张图是微球附件的PMMA的厚度分布的示意图，我们发现在靠近微球20微米的范围内PMMA急剧凸起，PMMA厚度分布满足 $h(r) = 1 + (\frac{R}{r})^4$

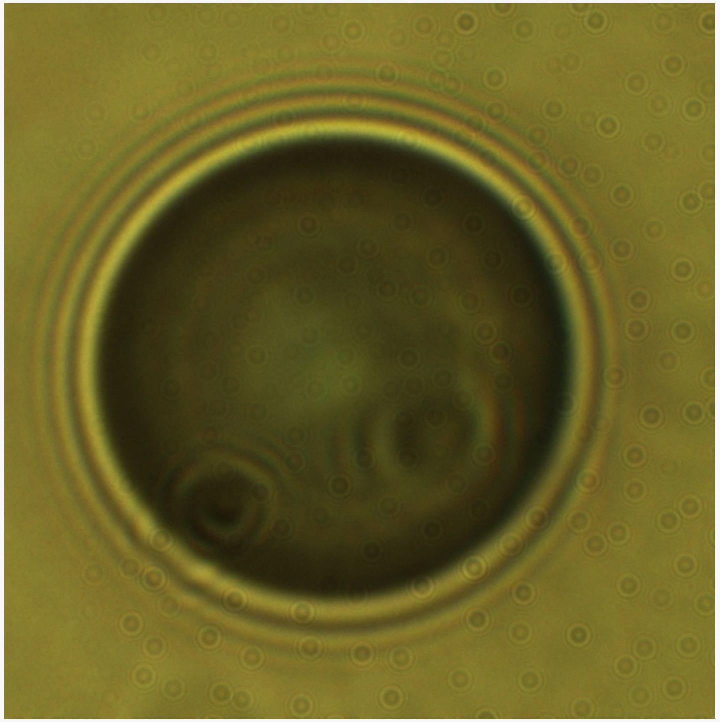
其中 $R \approx 26.54 \mu m$ 这个高度分布决定"黑洞"视界的大小是在微米的量级

弯曲波导的等效折射率的分布

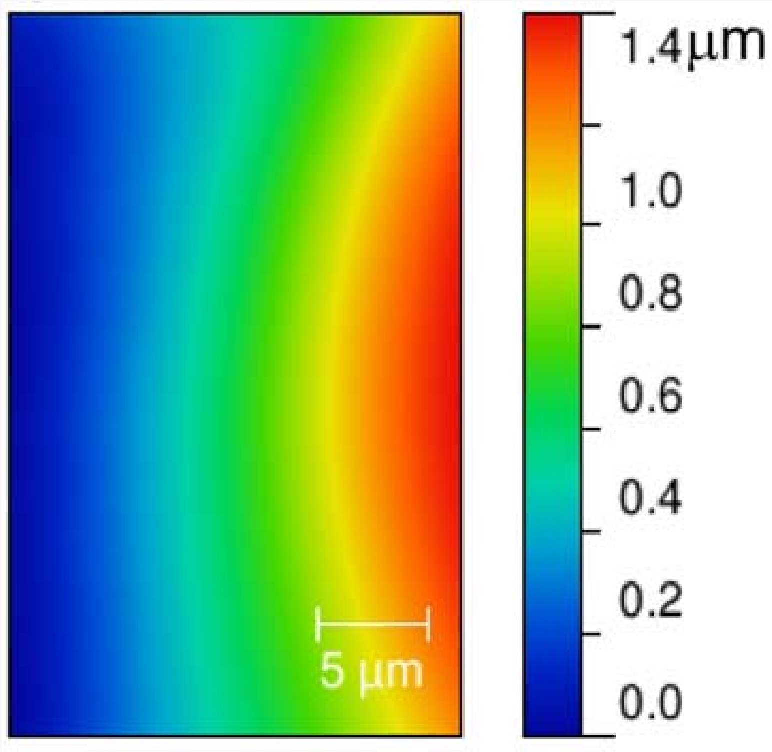


弯曲波导的表征

Interference pattern



AFM measurement



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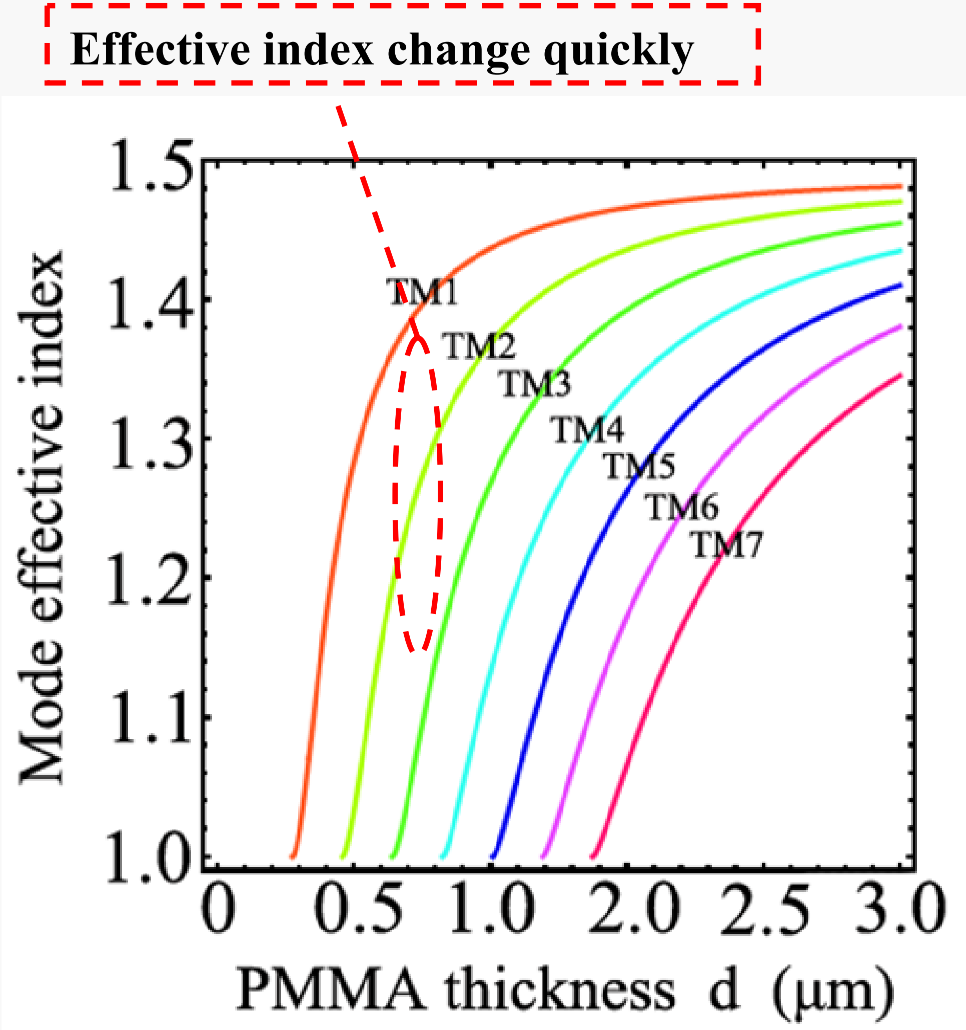
波导模的等效折射率



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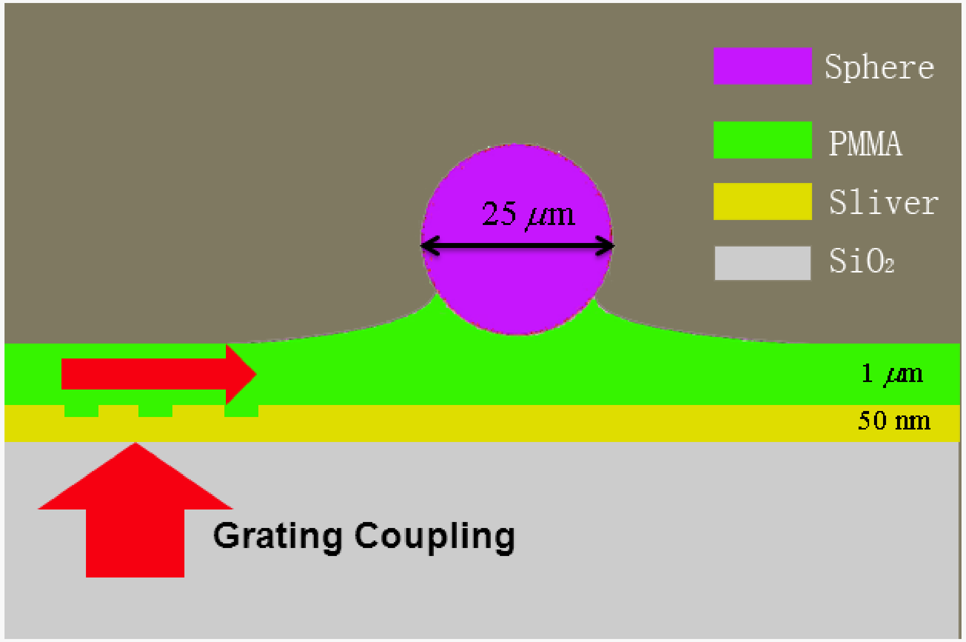
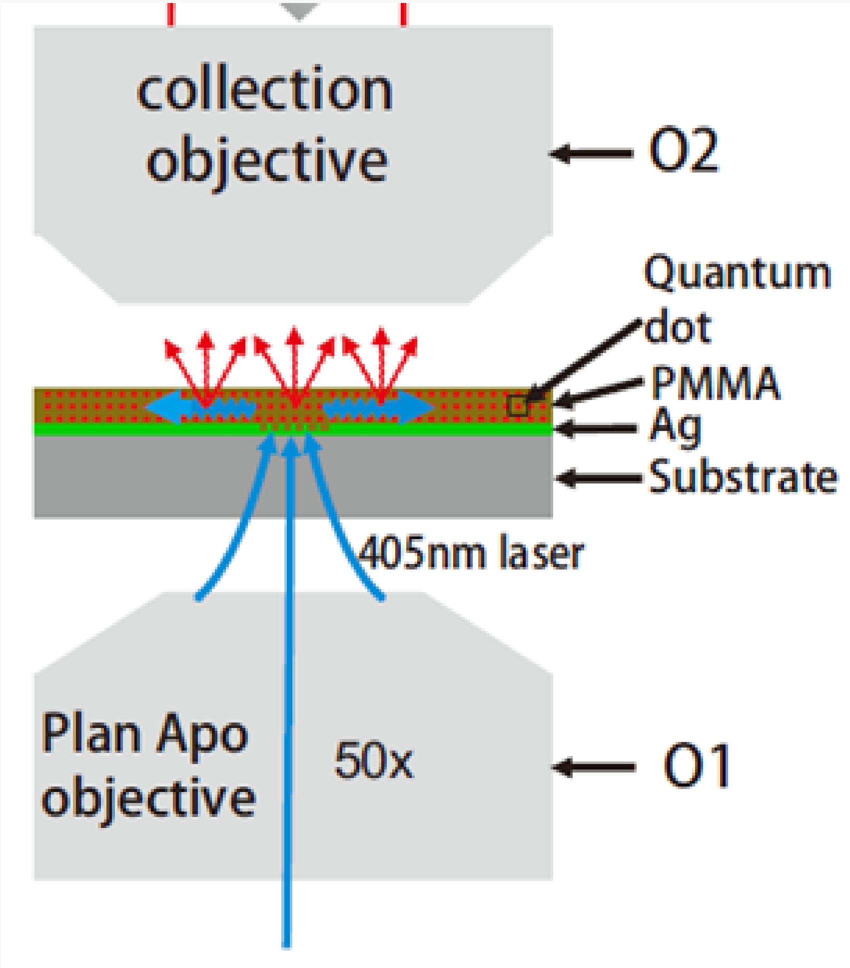
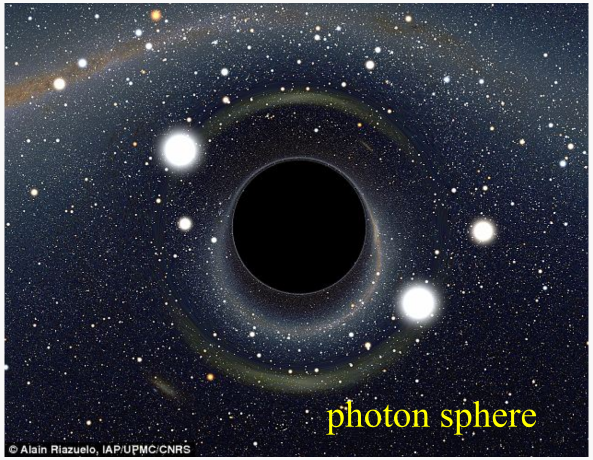
光学测量技术：量子点荧光成像法





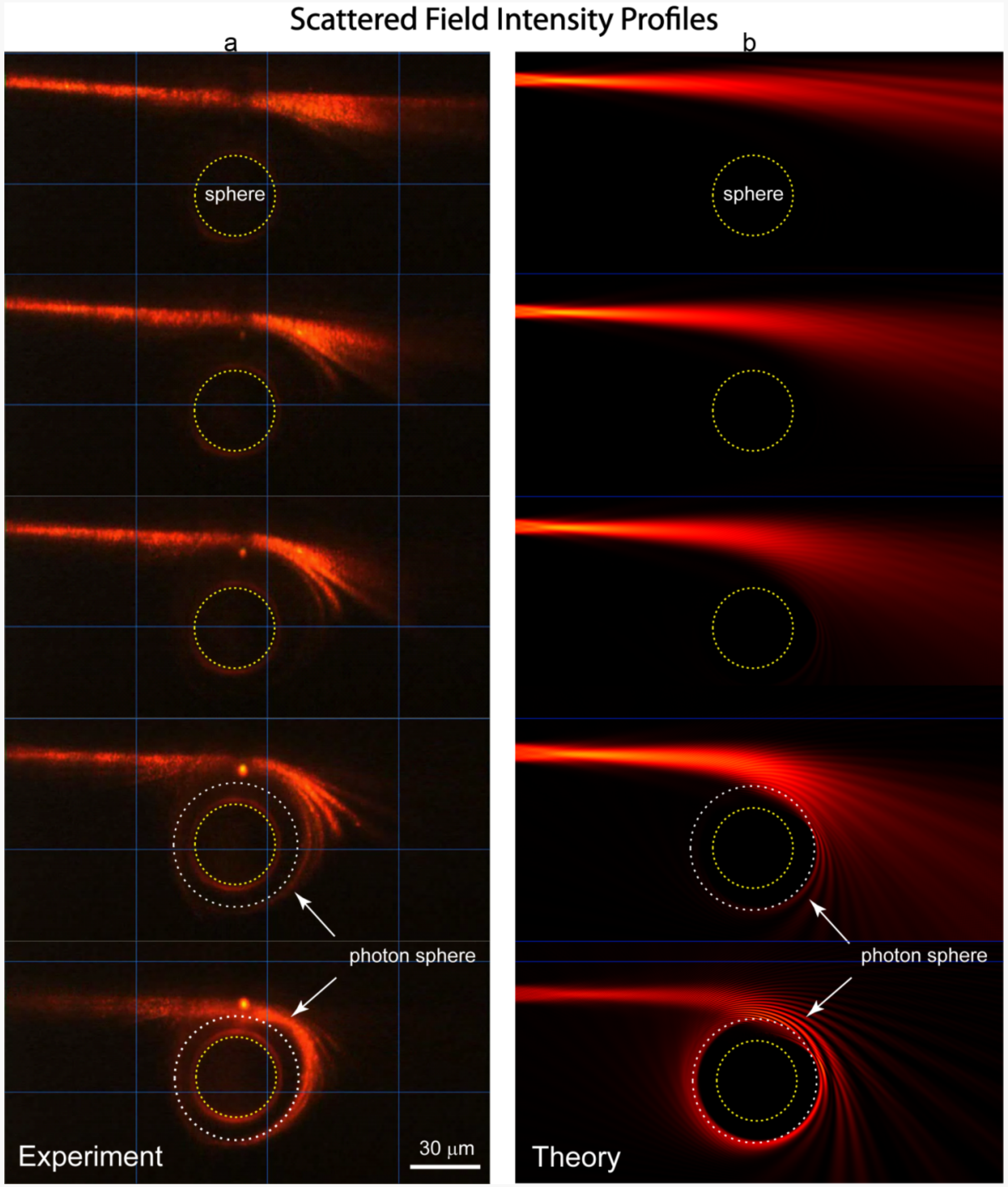
Nature Photonics, in press (2013)

光子捕获的临界半径



impact parameter r :
the perpendicular distance between the beam and the center of the microsphere

photon sphere r_c
(critical value r_c =39 um):
$r > r_c$ light deflected back into space
$r < r_c$ light captured by the "black hole"



基于爱因斯坦方程的理论计算

Thickness profile

$$h(r) \approx h_\infty \left(1 + \left(\frac{R}{r}\right)^4\right)$$

Effective refractive index

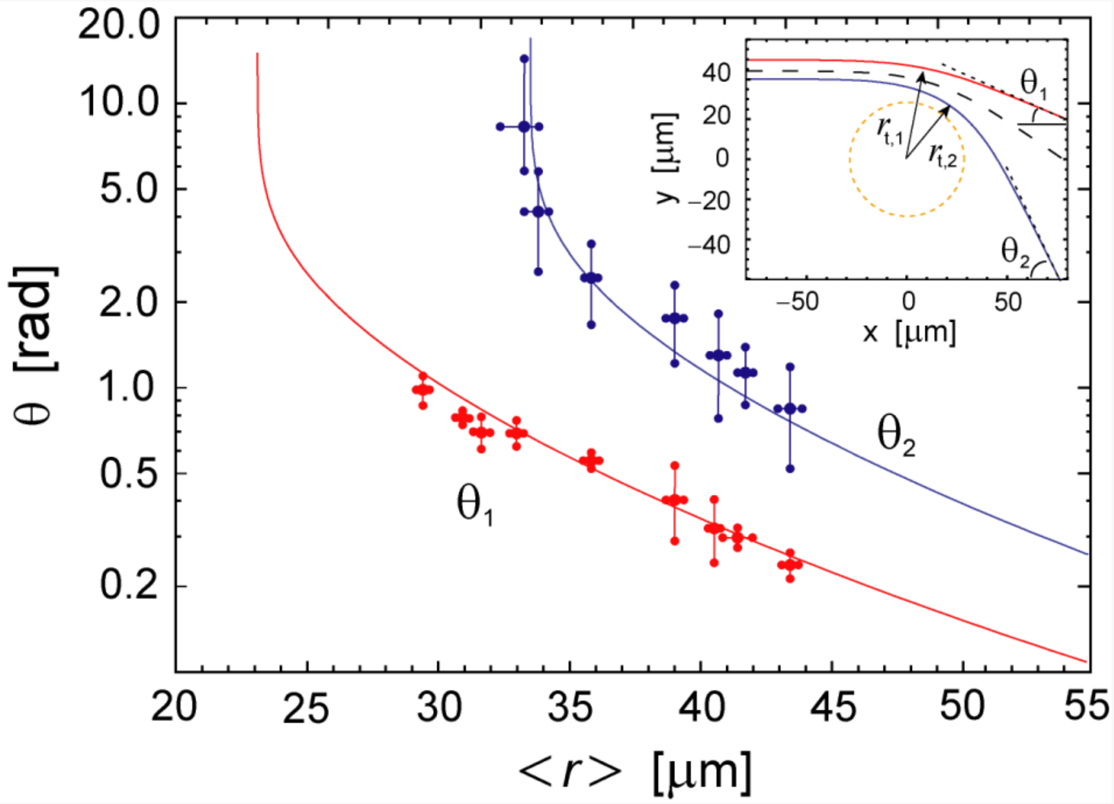
$$\varepsilon(r) = n^2(r) \approx n_\infty^2 \left[1 + \left(\frac{a}{r}\right)^4\right]$$

Equation of motion

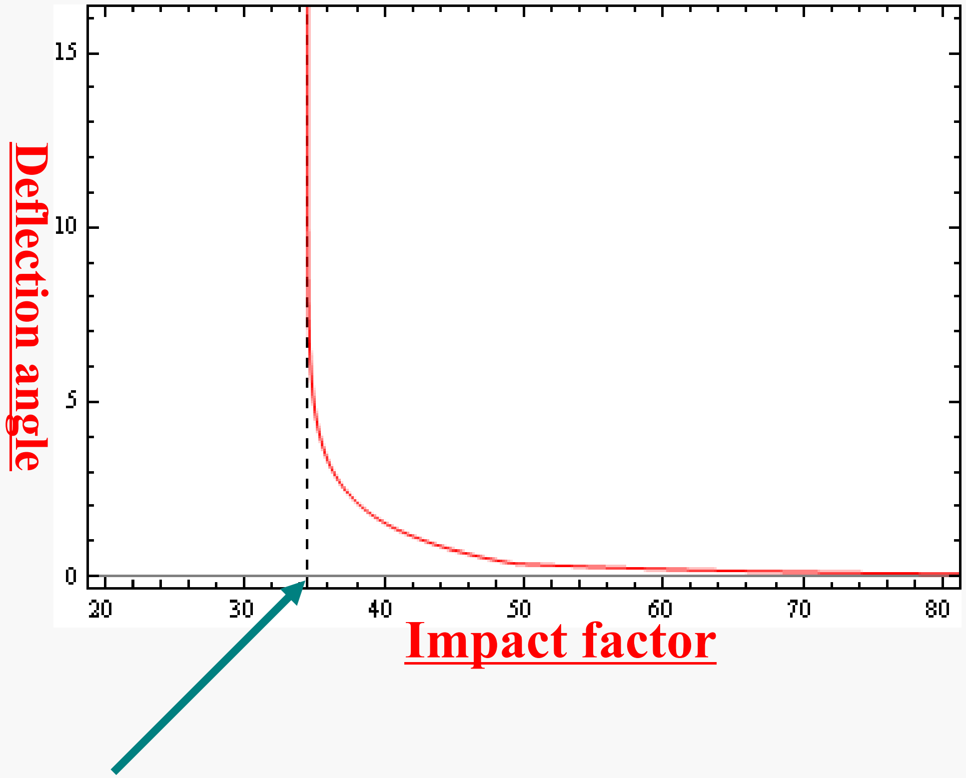
$$\left(\frac{dr}{d\varphi}\right)^2 = \frac{n^2(r) r^4}{b^2} - r^2$$

Deflection angle

$$\theta = 2K[u_t^4]\sqrt{1+u_t^4} - \pi$$



The deflection angles measured in the experiment (dots) and calculated (solid and dashed lines)



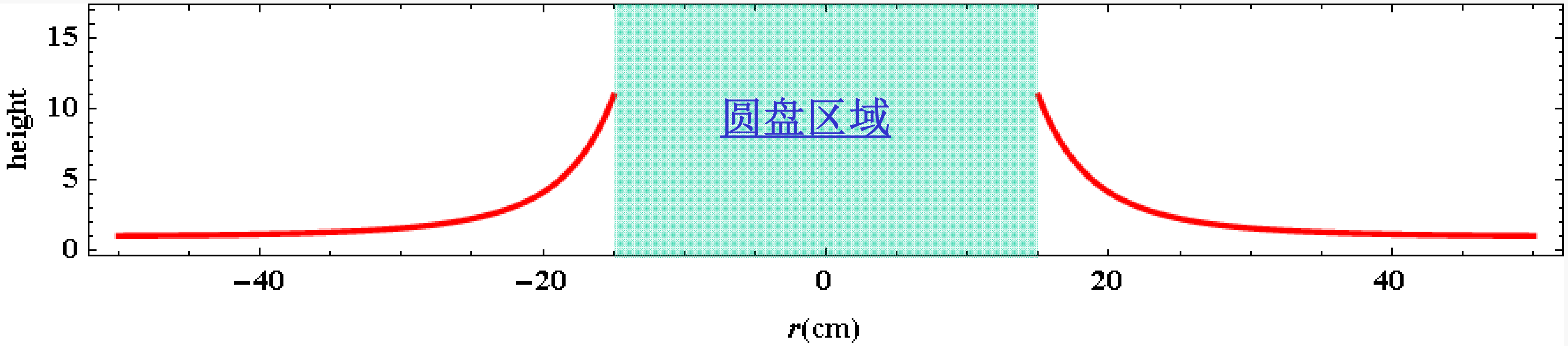
Photon sphere的半径

在photon sphere的半径处，偏折角无穷大，意味着在photon sphere处，光被trapping.

在直径为32cm的圆盘附近PMMA高度分布的参数分别为

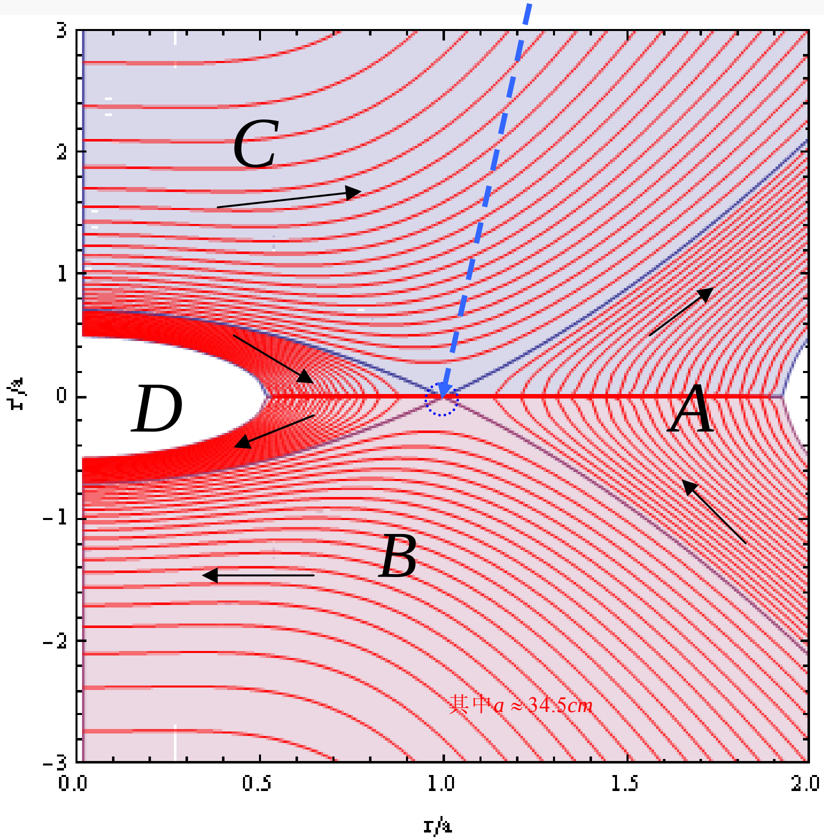
$$h(r) = h_{\infty}(1 + (\frac{R}{r})^{S})$$

$$h(r) = 1 + (\frac{30cm}{r})^{4} \ (\mu\text{m})$$



$h_{\infty} = 0.55\mu m$ R=30cm S=4

Photon sphere 对应半径处 $r_{ph} = a$



在 **photon sphere** 处满足

$$\frac{dr}{d\varphi} = 0 \quad \frac{d^2 r}{d^2\varphi} = 0$$

引力场分布是： $n^2(r) \approx 1 + \left(\frac{a}{r}\right)^4$

通过解方程，**photon sphere** 半径是：

$$a = 34.5cm$$

Phase space 图的说明：通过鞍点的等高线将相图分为四个部分，在区域A，光从无限远处来会被散射到无穷远处。在区域B中无限远处的光会吸引来“黑洞”附近，但是通过区域C最终逃逸出去，而只有在区域D光被trapping。

对于等效折射率分布为： $n(r) \approx \sqrt{1+\left(\frac{a}{r}\right)^4}$

Photon sphere 对应的半径是 $r_{ph} = a$

等效折射率梯度分布 $\left|\frac{dn}{dr}\right| = \frac{2a^4}{r^3\sqrt{a^4+r^4}}$

所以在 $r_{ph} = a$ 梯度的数值为 $\left|\frac{dn}{dr}\right|_{r=r_{ph}} = \frac{2a^4}{r^3\sqrt{a^4+r^4}} = \frac{\sqrt{2}}{a}$

在**photon sphere** 处折射率的导数都是 $\frac{\sqrt{2}}{a}$

在文章中，折射率分布和最近假设的等效折射率分布形式相同，所以数值是一样的。只不过是半径的单位不同，一个是微米，一个是厘米

表 4.1　典型天体的密度与表面引力场强度

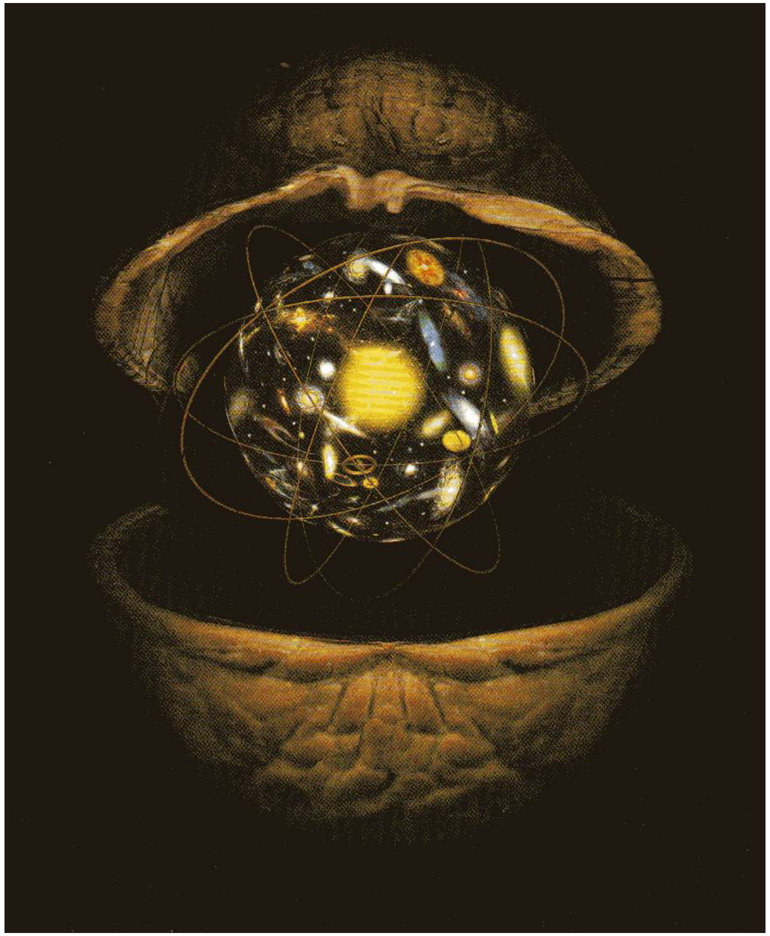
天体名称	平均密度(g/cm^3)	引力强度参数($2GM/Rc^2$)
地球	5	10^{-9}
太阳	1	10^{-6}
白矮星	$\sim 10^6$	$\sim 10^{-4}$
中子星	$\sim 10^{14}$	$\sim 10^{-1}$
黑洞		1

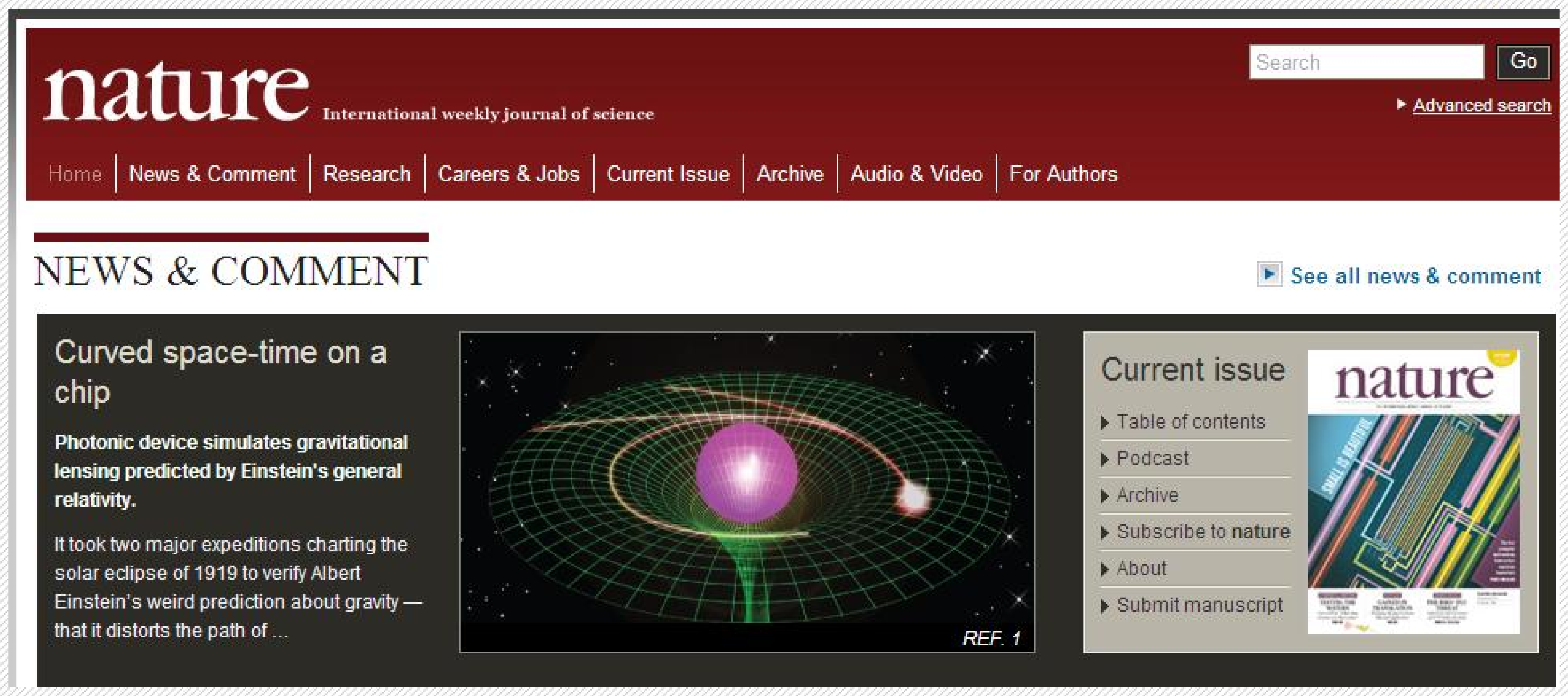
对于黑洞表面引力强度 = $2GM / Rc^2$ $= a / R = 1$

$$a \equiv 2GM / c^2$$

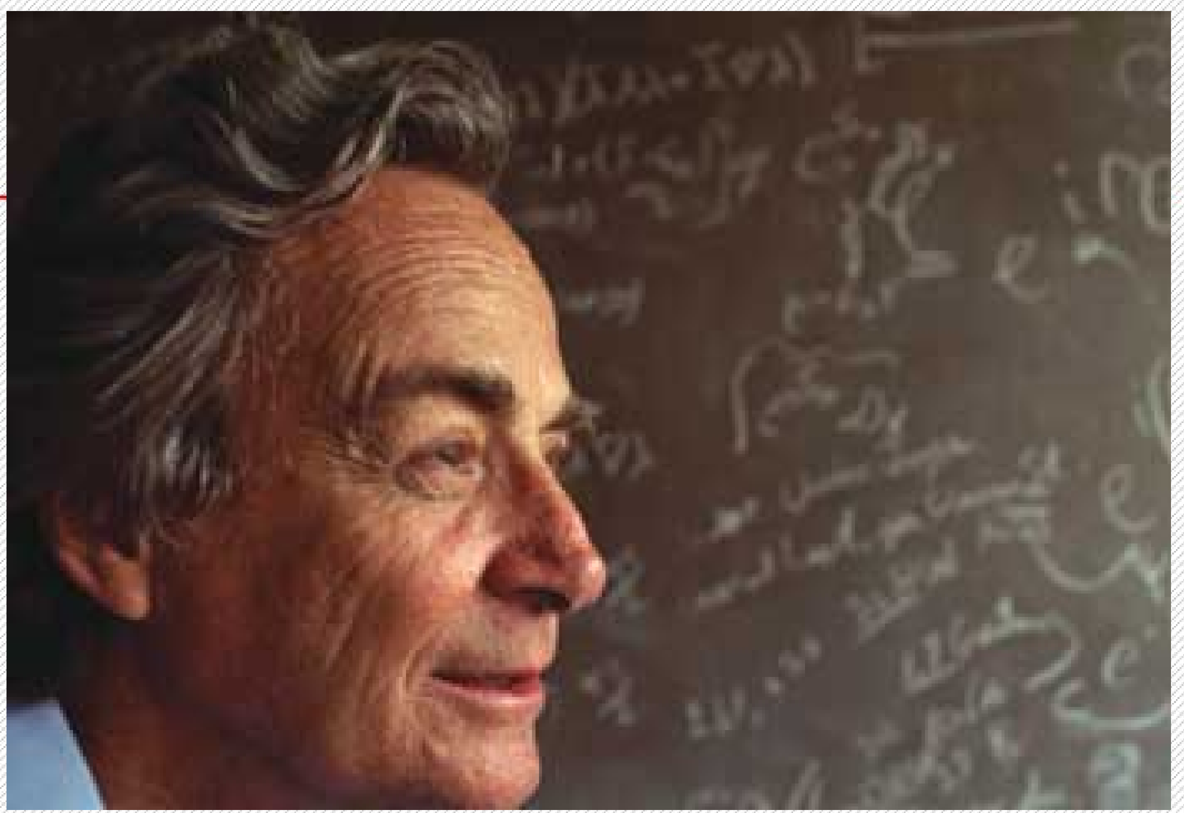
$$\rho \propto M / a^3 \propto 1 / M^2$$

1. M = 10 ^{15} g, *r = 1.5 * 10^{-13} cm => 10^{53} g / cm^3;*
2. M = *3* 10^{55} g, r = 4 * 10^{27} cm (10^{10}) => 10^{-29}g / cm^3.*





"This is indeed the first time an exact solution of Einstein's equations was mimicked" using an optical model, says Leonhardt. The simplicity of the experiment — microspheres on plastics — "beautifully illustrates some of the ideas of general relativity", he adds.



Richard Feynman

Still, says study coauthor Dentcho Genov of Louisana Tech University in Ruston, the team's microchip model "may hold the key to the elucidation of phenomena based on general relativity that are extremely difficult to study through direct astronomical observations". This includes cases of radio waves with wavelengths comparable to the size of the celestial object, he notes.

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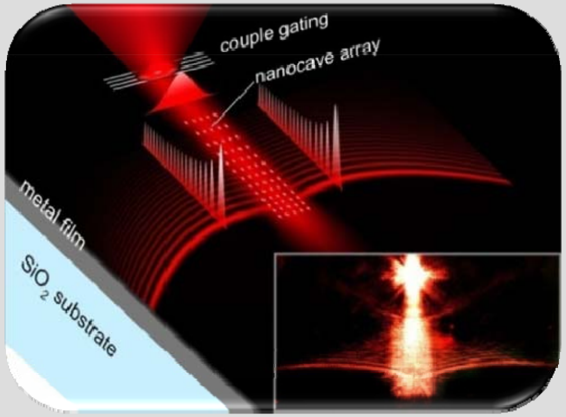

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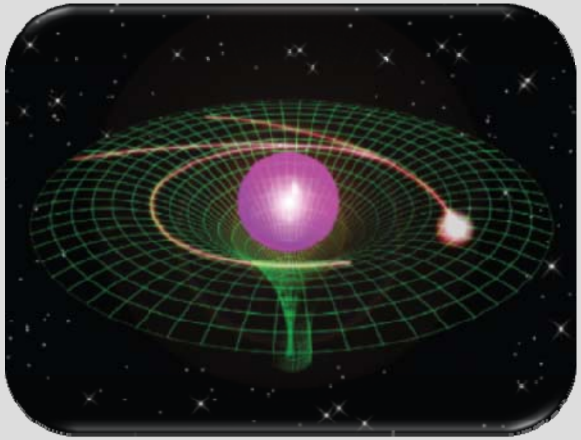

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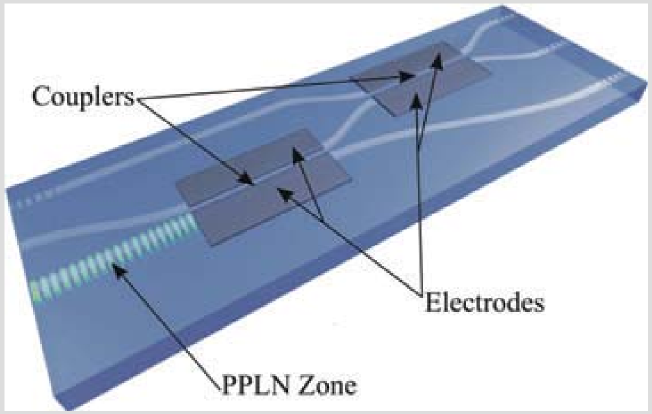

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