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Quantum super-resolution using entangled photons

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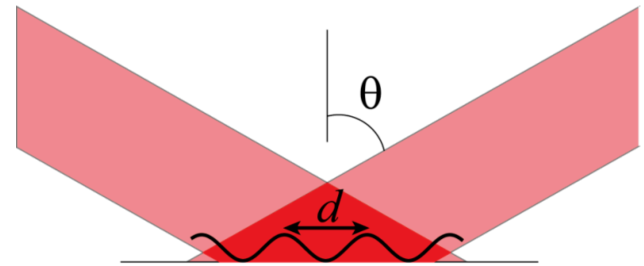
Introduction

- Imaging resolution is limited by diffraction (i.e. interference).
- Recording wavelength: λ = 800 nm
- Standard classical limit: $d = \lambda / 2$ = 400 nm



Can we record 200-nm ($\lambda/4$) periodic patterns with 800-nm light beating the classical limit?

- Using entangled photons

- A. N. Boto, *et al.*, Phys. Rev. Lett. 85, 2733 (2000).
- M. Tsang, Phys. Rev. Lett. 102, 253601 (2009).

Entanglement

- Non-classical phenomenon started from EPR paradox

- e.g. subatomic particle decay: $\phi^{\uparrow} \leftarrow \bigcirc \rightarrow \phi_{\downarrow}$ or $\phi_{\downarrow} \leftarrow \bigcirc \rightarrow \phi^{\uparrow}$

- Quantum superposition: only way to describe two objects

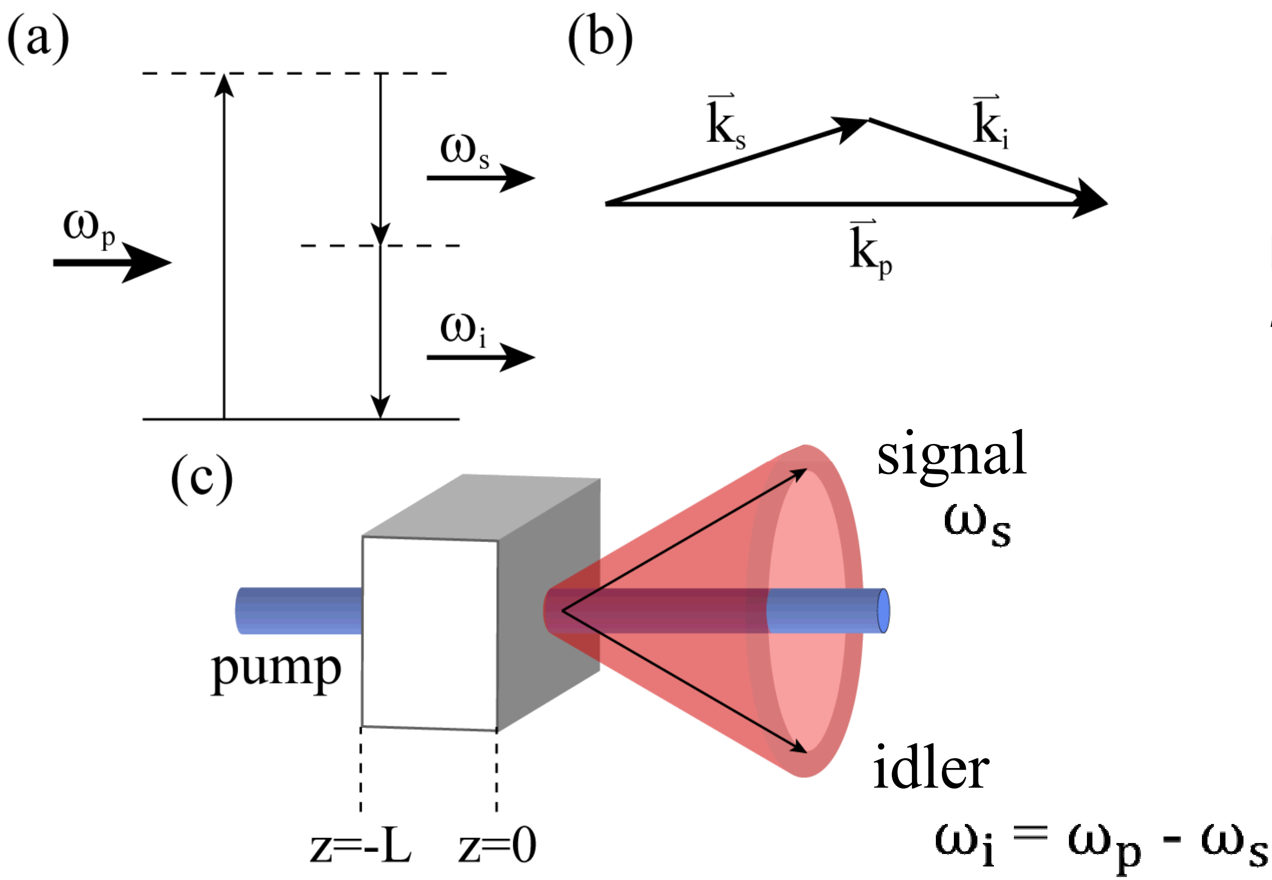
$$|\phi^{\uparrow}\rangle_{\text{left}}|\phi_{\downarrow}\rangle_{\text{right}} + |\phi_{\downarrow}\rangle_{\text{left}}|\phi^{\uparrow}\rangle_{\text{right}}$$

- No $|\phi^{\uparrow}\rangle_{\text{left}}|\phi^{\uparrow}\rangle_{\text{right}}$, $|\phi_{\downarrow}\rangle_{\text{left}}|\phi_{\downarrow}\rangle_{\text{right}}$

- When one of them is measured, immediately the state of another particle is determined.

How to create entangled photons 1

Spontaneous parametric down conversion



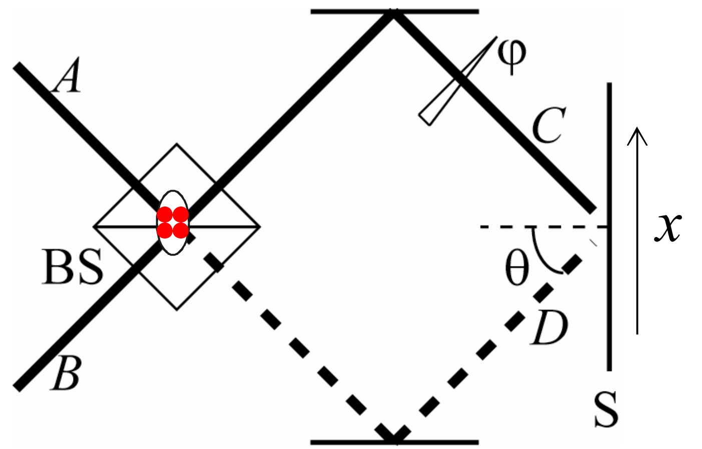
Robert W. Boyd,
Nonlinear Optics, 3rd ed.

How to create entangled photons 2

The $N00N$ states

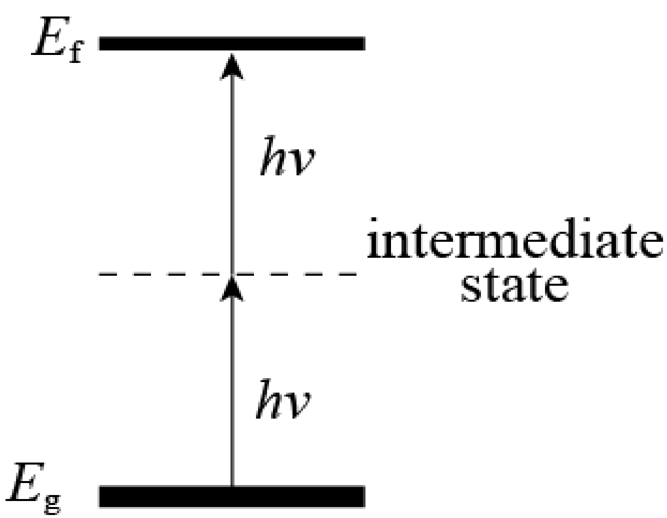
- Path-entangled photon-number states

$$\frac{1}{\sqrt{2}}\left(e^{Ni\varphi}\left|N,0\right\rangle_{C,D}+\left|0,N\right\rangle_{C,D}\right)=\left|N00N\right\rangle$$

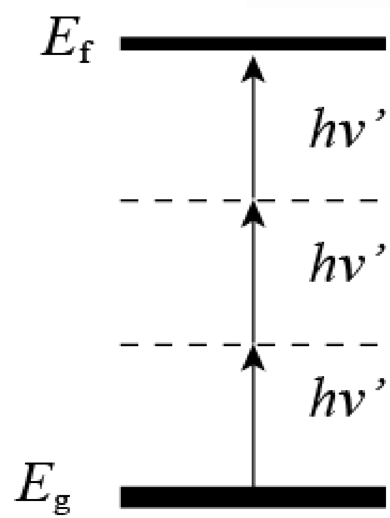


$$\varphi = 2\pi \sin\theta \; x / \lambda$$

- Multi-photon absorption material



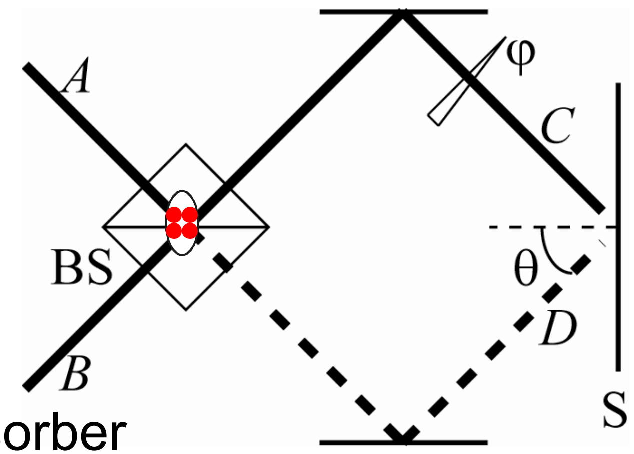
2PA process



3PA process

Quantum lithography

- Quantum lithography
  - The $N00N$ states
  - Multi-photon absorption (MPA) material



$\varphi = 2\pi \sin\theta\, x / \lambda$

- The pattern recorded in an *N*-photon absorber

$$I \propto \langle N00N | \hat{e}^{+N} \hat{e}^{N} | N00N \rangle \propto \cos^2(N\varphi)$$

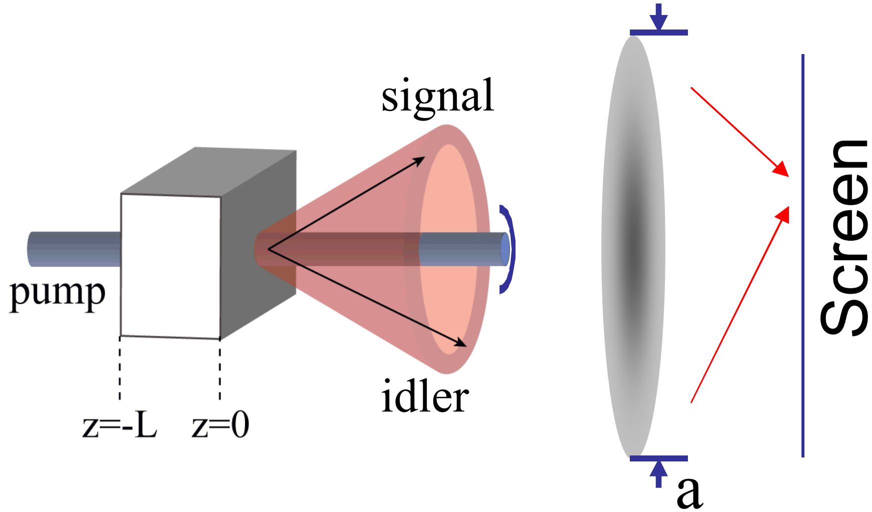
$\hat{e}$: the photon annihilation operator on screen.

- The period of the interference fringe pattern

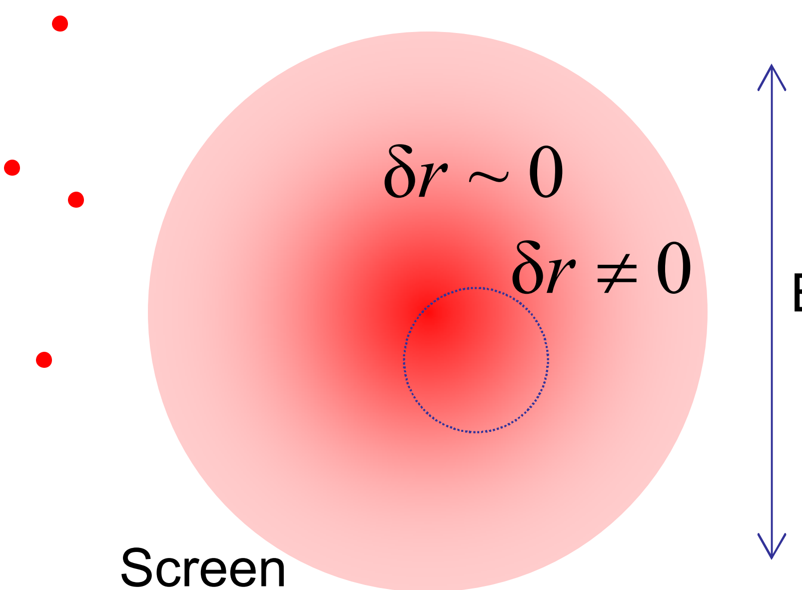
$$d = \lambda / (2N \sin\theta)$$

A. N. Boto, *et al*., Phys. Rev. Lett. **85**, 2733 (2000)

Correlation area



- In the image plane of the crystal



– pump beam uncertainty

$\Delta k_{pump\perp} \neq 0$

– phase mismatch, $L \neq \infty$

$\vec{k}_{pump} - \vec{k}_{sig} - \vec{k}_{idler} = \Delta\vec{k} \neq 0$

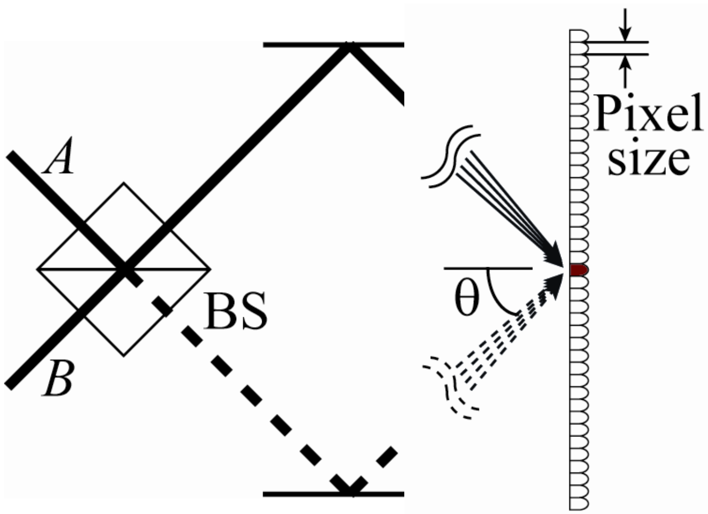
– point spread function

$a \neq \infty$

- Random position on the screen within the correlation area.

Quantum imaging using MPA

- Large detector size and high quantum efficiency
- An array of MPA detectors and a $N00N$ state



- *N* photons arriving at an *N*-photon detector array through either solid or dashed path
- Only when *N* photons fall on one pixel, the MPA detector array counts the events.

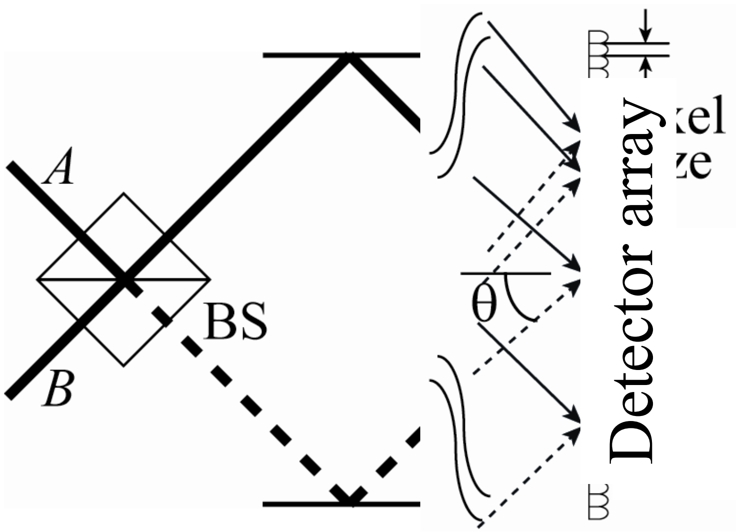
- A histogram of the positions of MPA events

$$d = \frac{\lambda}{2N \sin \theta}$$

A. N. Boto, *et al*., Phys. Rev. Lett. **85**, 2733 (2000)

Optical centroid measurement (OCM)

- Quantum super-resolved imaging method without MPA
  - M. Tsang, Phys. Rev. Lett. 102, 253601 (2009).

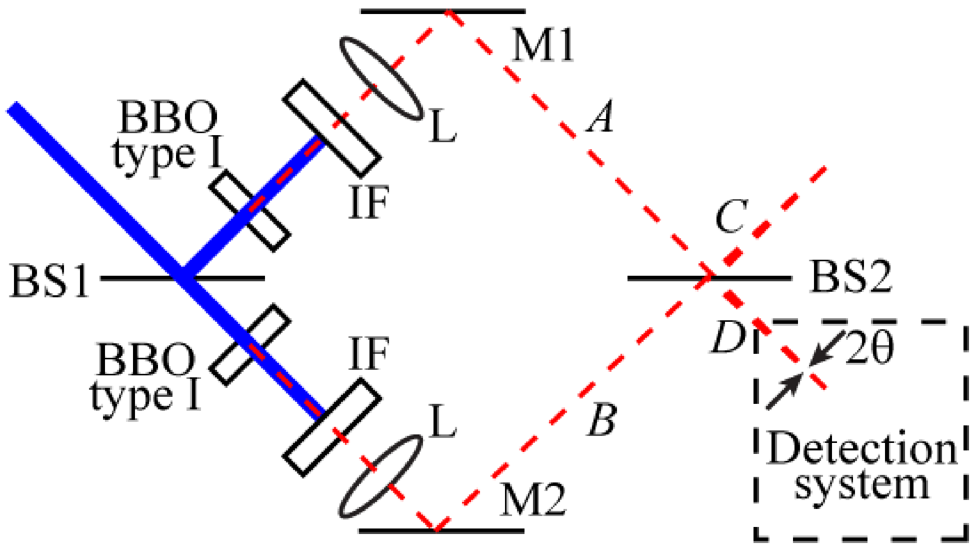


- N photons arriving at single-photon detector array through either solid or dashed path.
- Large correlation area
- Optical centroid position from the addresses of the N pixels

- A histogram of the positions of optical centroids

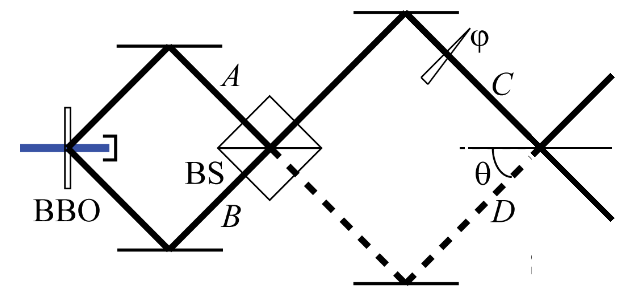
$$d = \frac{\lambda}{2N \sin\theta}$$

Experiment



IF: interference filter, D: detector system

- SHG 100 fs pulses at 400 nm with 82-MHz rep. rate
- No need to make HOM setup



- Collinear type I phase matching

- The photon state in modes *A* and *B*

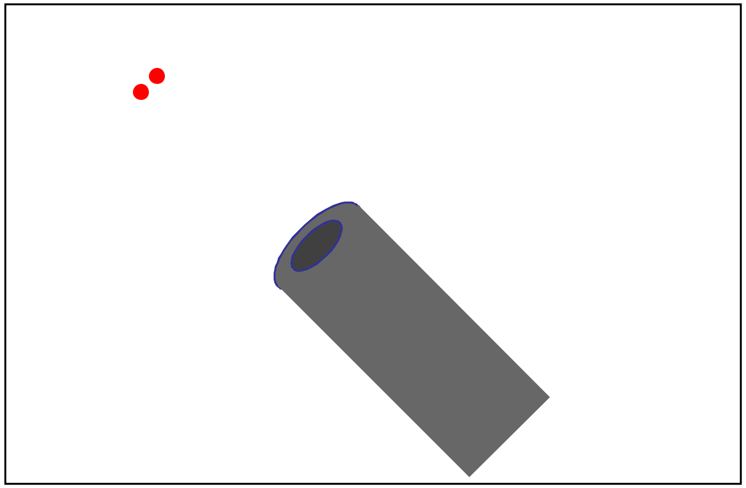
$$|\Psi\rangle = |0\rangle_A|0\rangle_B + \eta\left(|2\rangle_A|0\rangle_B + |0\rangle_A|2\rangle_B\right)/\sqrt{2} + \eta^2\left(|4\rangle_A|0\rangle_B + |0\rangle_A|4\rangle_B + \sqrt{2}|2\rangle_A|2\rangle_B\right)/\sqrt{4}$$

- For $N = 2$ case, $\eta \ll 1$ and η^2 can be ignored.

$$|\Psi\rangle \approx \eta\left(|2\rangle_A|0\rangle_B + |0\rangle_A|2\rangle_B\right)/\sqrt{2}$$

Detection systems

• Two-photon detector



- Photon pairs arrive at one fiber.

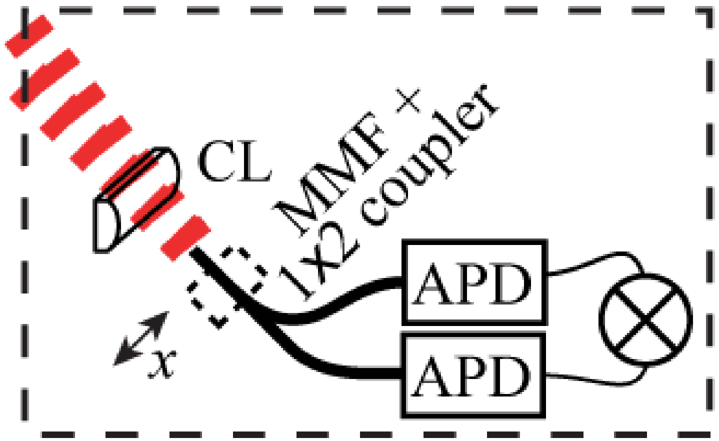
- Two-photon absorption

- Recording the coincidence counts while scanning the input fiber in discrete steps along x.

• Optical centroid detector

Detection systems

- Two-photon detector



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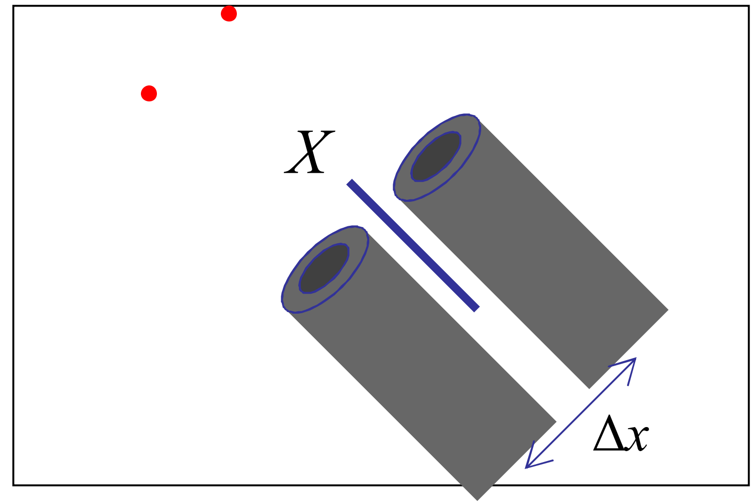


- Photon pairs arrive at two fibers of a given separation Δx.

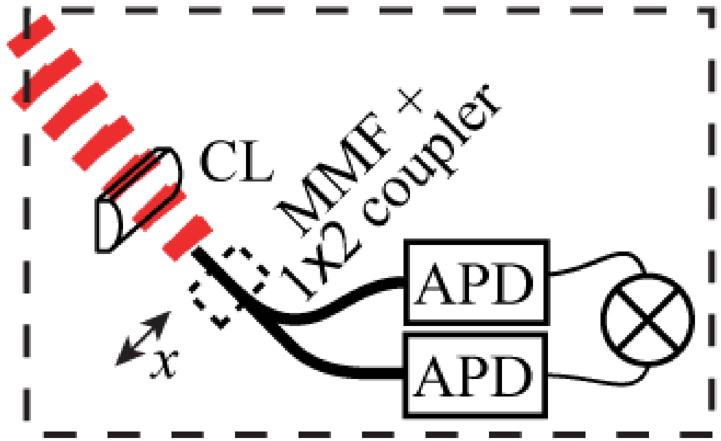
- The optical centroid position is at midpoint between two fibers.

- This fiber pair is scanned along X.

- Variable separation

Detection systems

• Two-photon detector



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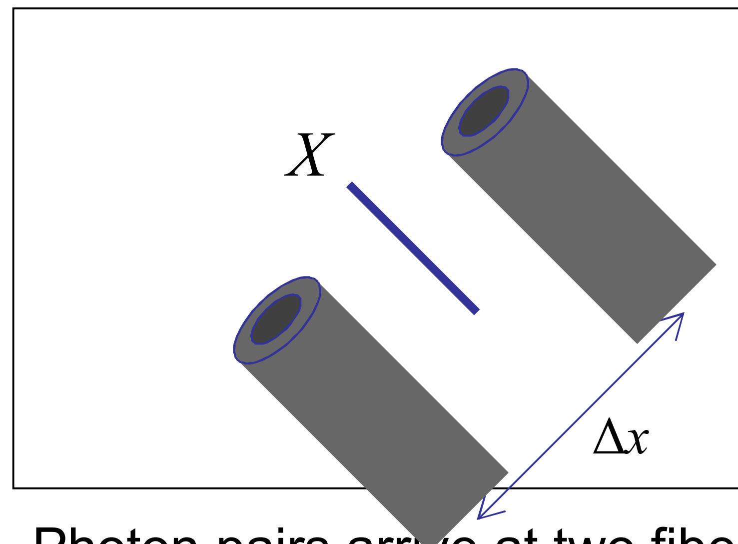

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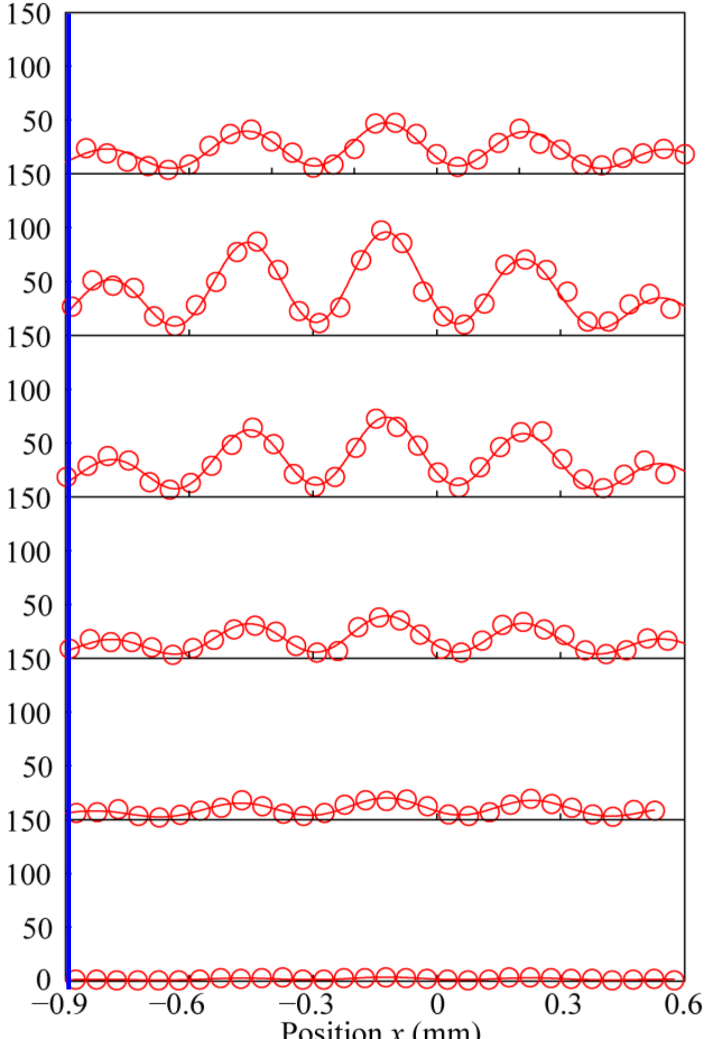
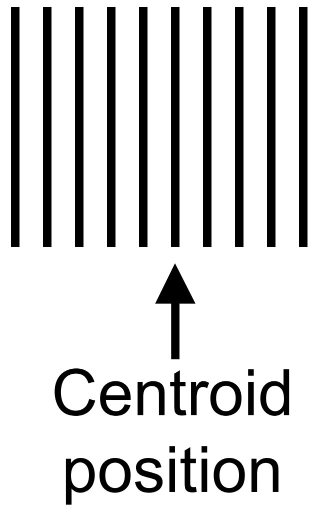
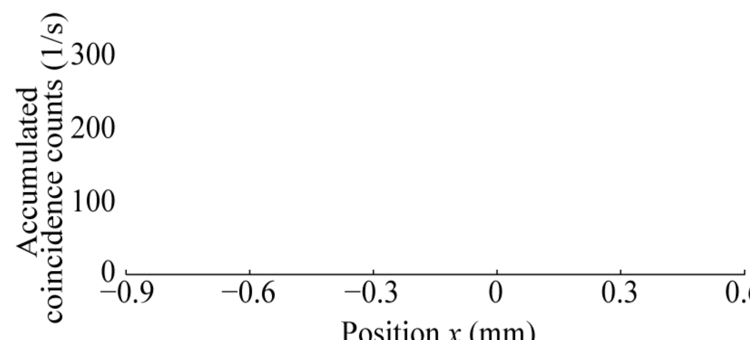
Experimental result

- Various fiber separations







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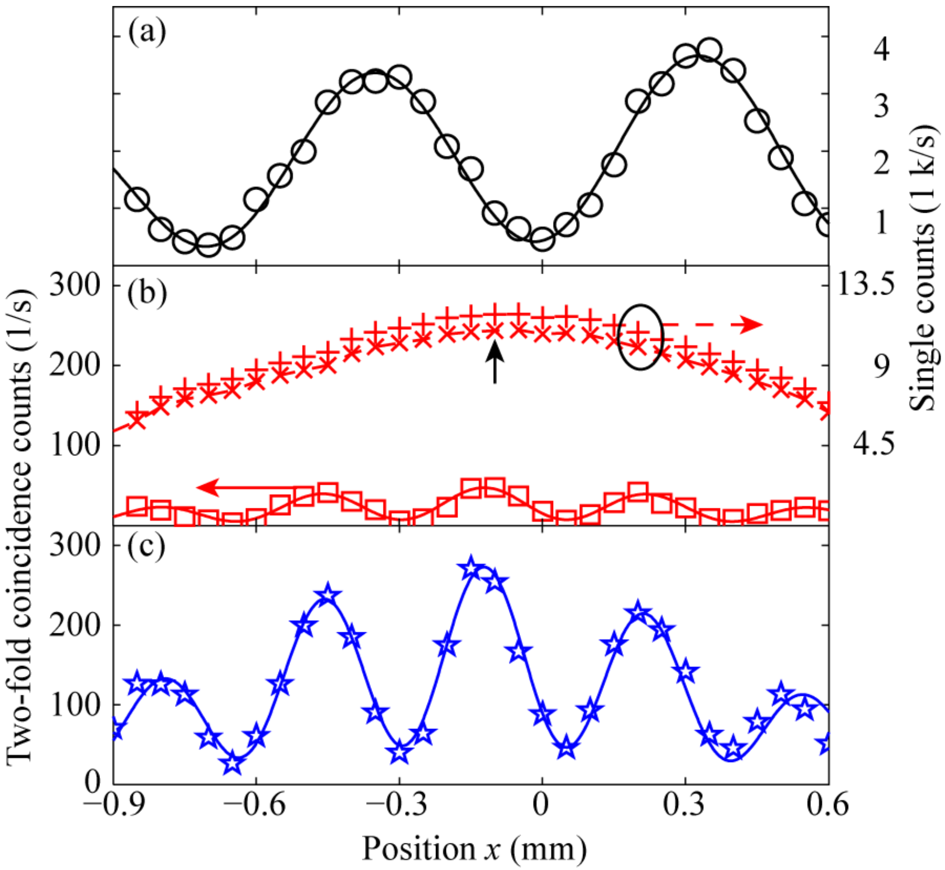


- Single photons at 800 nm
  d = 0.69 mm
- Photon pairs at 800 nm detected by the two-photon detector
  d = 0.34 mm
- Photon pairs at 800 nm detected by PNR optical centroid detector.
  d = 0.34 mm

- Amplitude of the interference pattern for OCM is about 6 times larger than that for MPA.

Conclusion

- Demonstration of spatial resolution enhancement by a factor of $N = 2$.
- Quantum imaging with MPA and OCM
- Higher efficiency of OCM than MPA

Heedeuk Shin, Kam Wai Clifford Chan, Hye Jeong Chang, and Robert W. Boyd, "Quantum spatial super-resolution by the optical centroid measurement method," Physical Review Letters **107**, 083603 (2011)

- Higher N > 2 resolution enhancement
- Quantum metrology, photon number-resolving detection, and quantum correlated imaging,

Thank you for your attention!

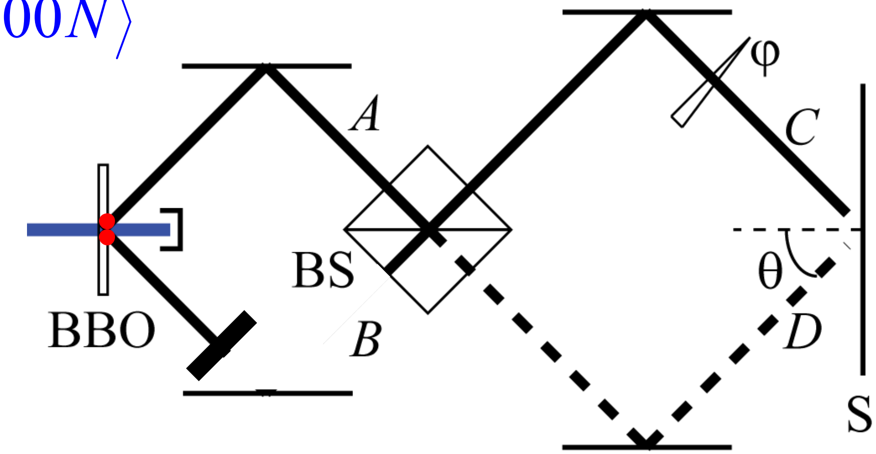
Heedeuk.shin@gmail.com

How to create entangled photons 2

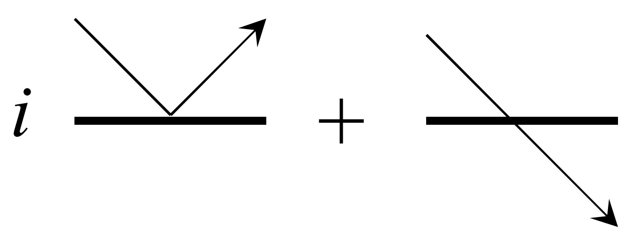
- Path-entangled photon-number states

$$\frac{1}{\sqrt{2}}\left(e^{Ni\varphi}|N,0\rangle_{C,D}+|0,N\rangle_{C,D}\right)=|N00N\rangle$$

$$\varphi = 2\pi \sin\theta \; x/\lambda$$



- Possible cases



C. K. Hong, *et al.*, Phys. Rev. Lett. **59,** 2044 (1987).

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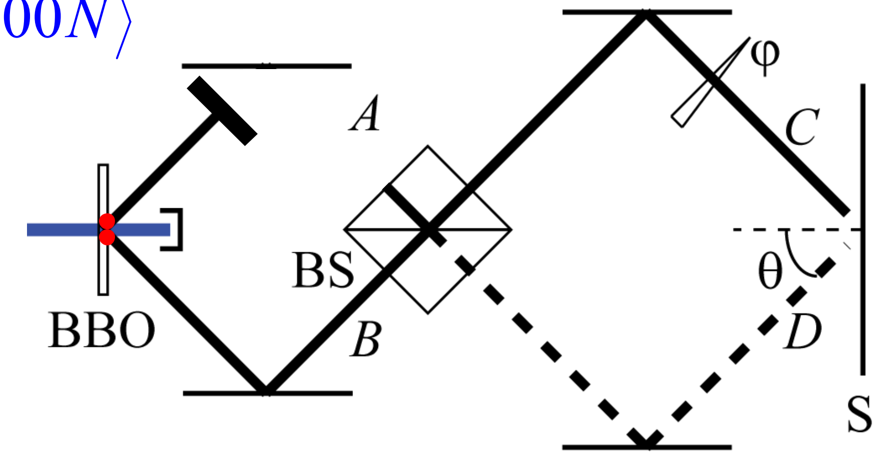

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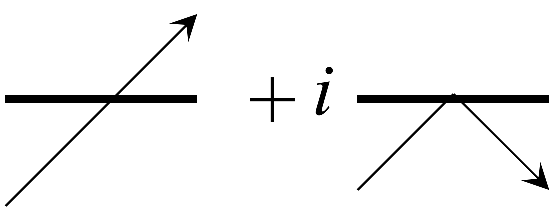

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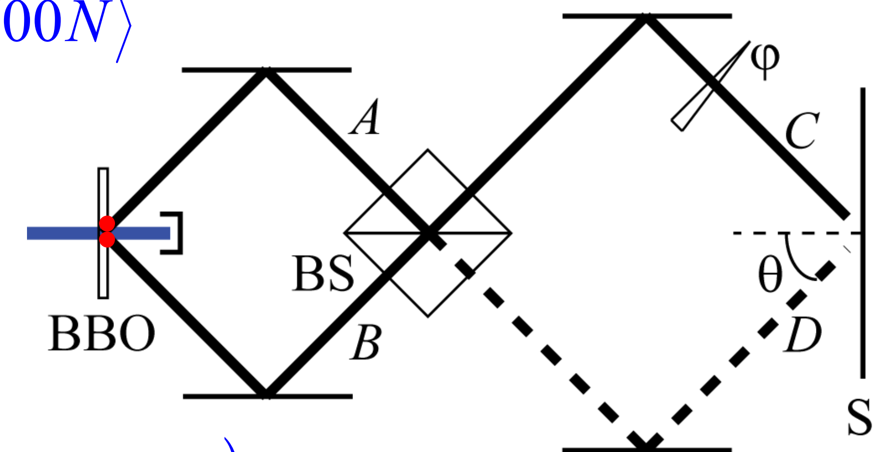
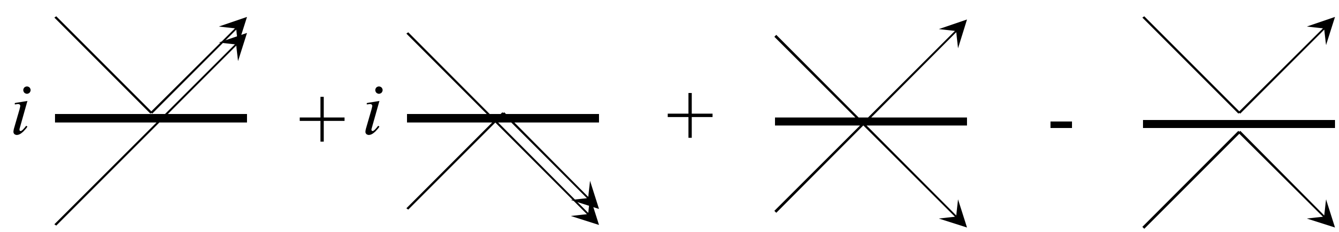


- The Hong-Ou-Mandel effect
  - A two-photon interference effect

- Possible cases

$$\frac{1}{\sqrt{2}}\left(e^{2i\varphi}\left|HH,0\right\rangle_{C,D}+\left|0,HH\right\rangle_{C,D}\right)\equiv\left|2002\right\rangle$$



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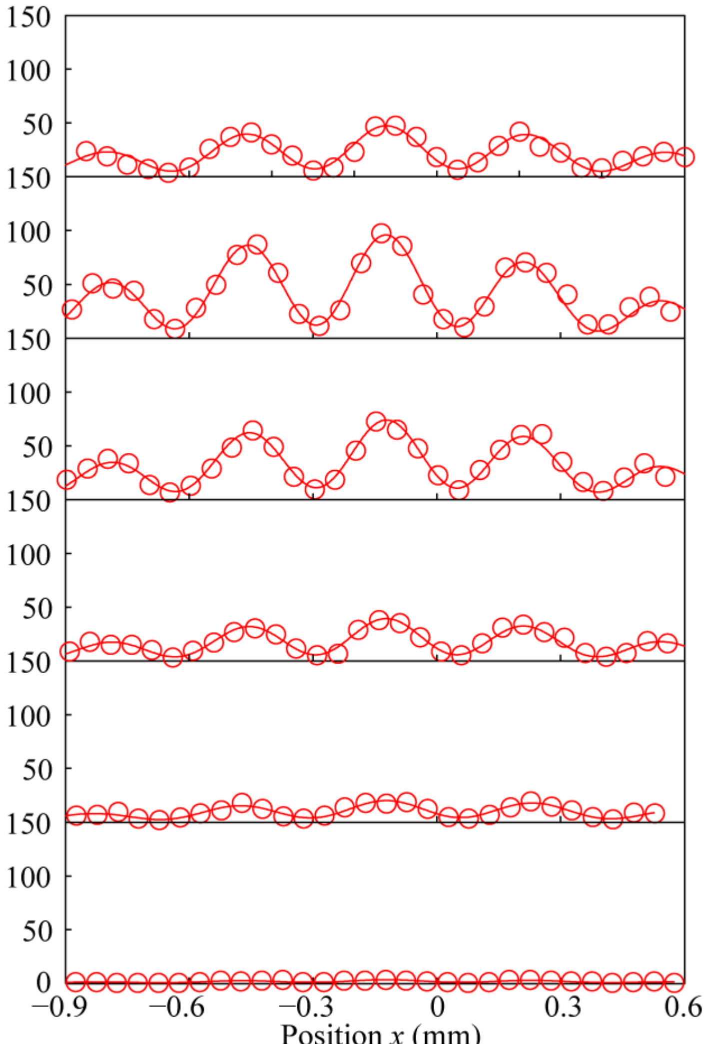
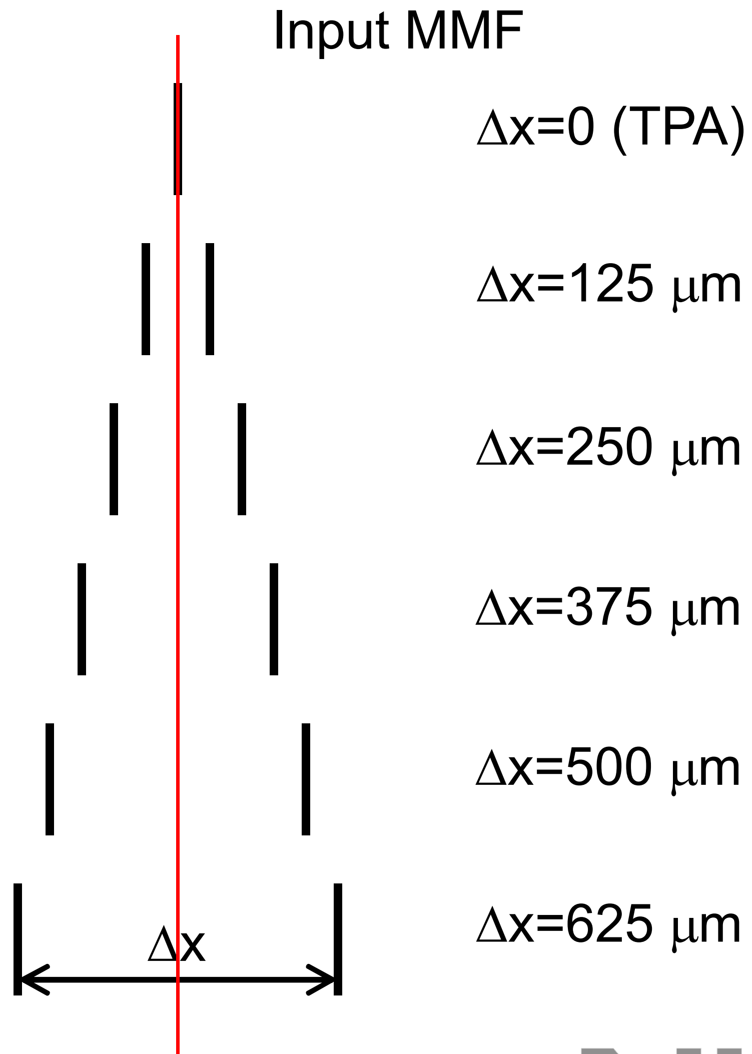
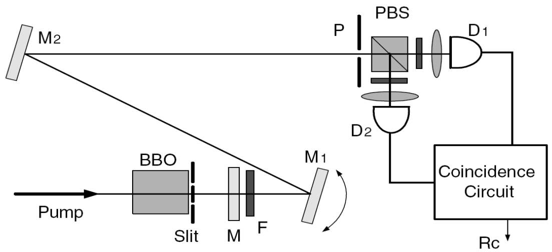
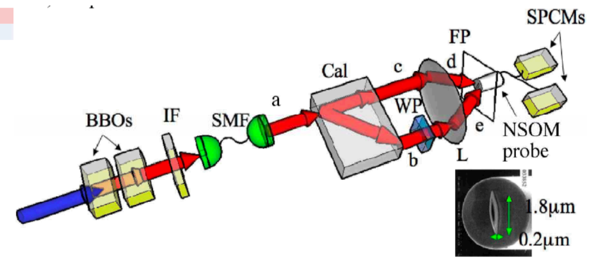
- Various fiber separations





Experimental demonstration of Quantum lithography





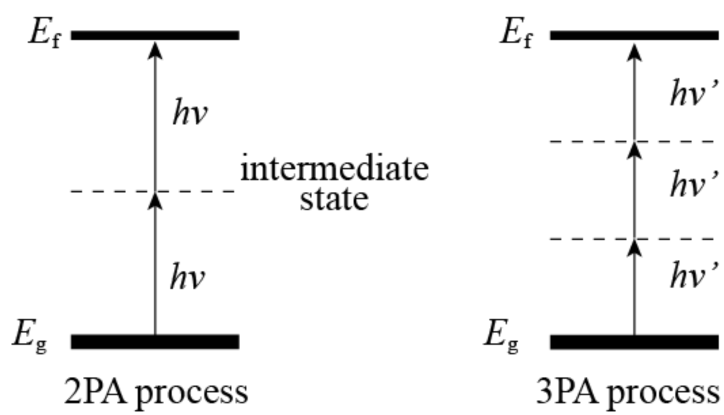
M. D'Angelo, M. V. Chekhova, and Y. Shih

Phys. Rev. Lett. 87, 013602 (2001)

Y. Kawabe, H. Fujiwara, R.Okamoto, K. Sasaki, and S. Takeuchi

Opt. Express 15, 14244 (2007)

- Multi-photon absorption (MPA) is a multi-step process.



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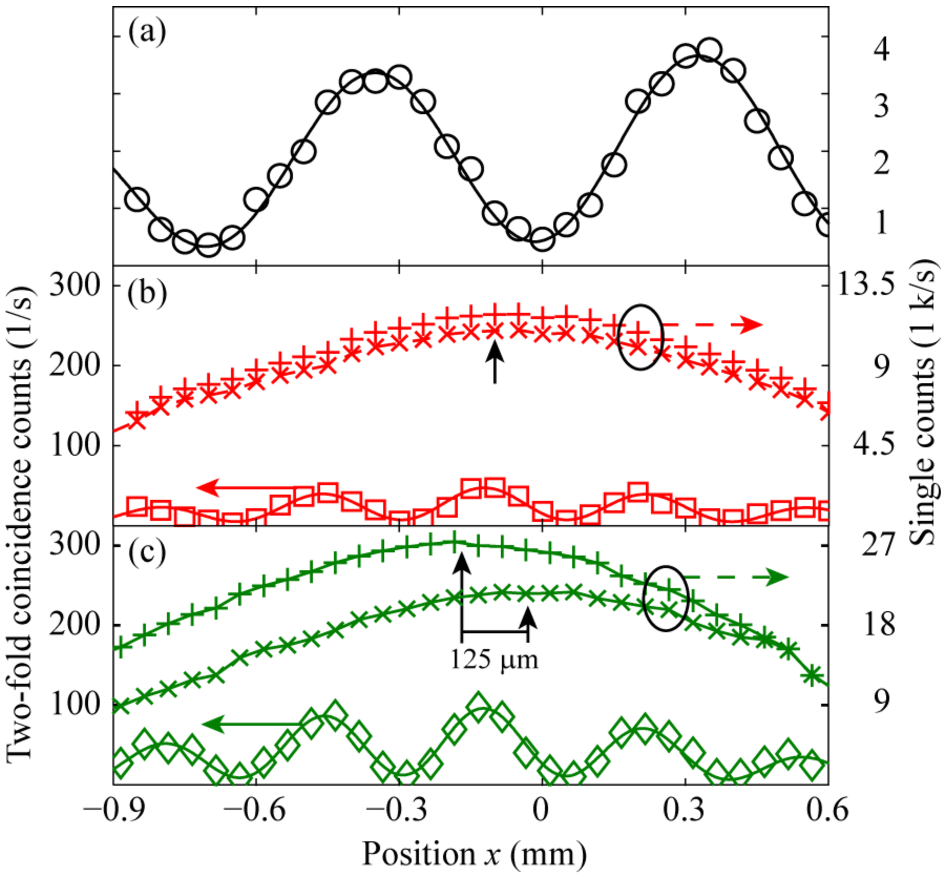

- Single photons at 800 nm
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  d = 0.34 mm
- Photon pairs at 800 nm detected by the optical centroid detector for Δx = 125 μm.
  d = 0.34 mm