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Entanglement swapping over 100 km optical fiber with independent entangled photon-pair sources and Experimental demonstration of nonbilocality

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Outline

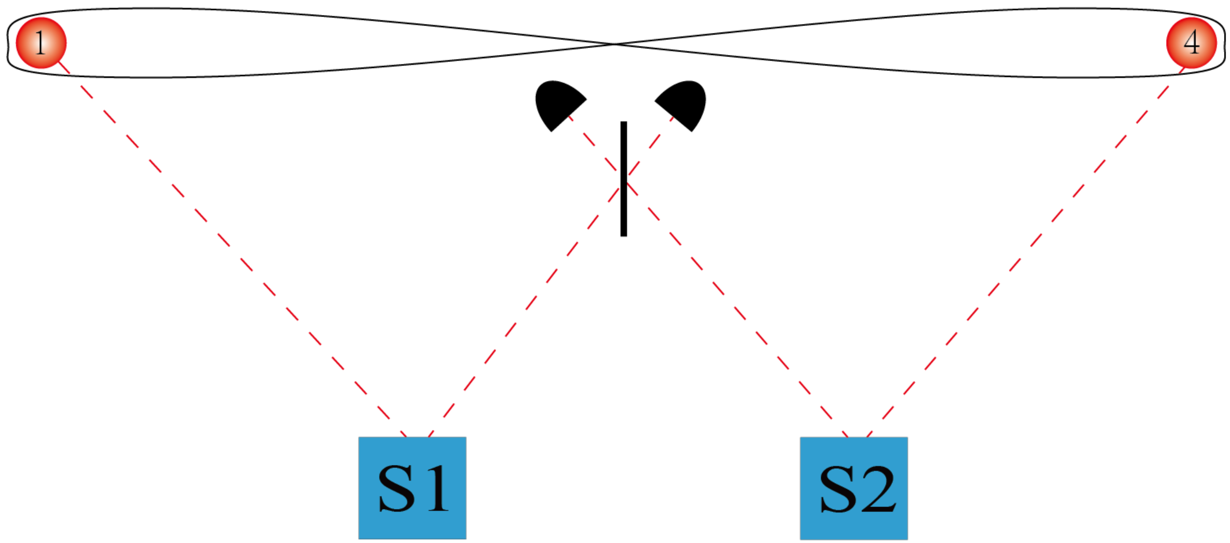
① A brief review on Entanglement swapping

② Entanglement swapping over 100 km optical fiber

③ Experimental demonstration of nonbilocality

④ Summary and outlook

A brief review on Entanglement swapping



EPR-sources

$$|\Psi\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)$$

$$|\Psi\rangle_{34} = \frac{1}{\sqrt{2}}(|H\rangle_3|V\rangle_4 - |V\rangle_3|H\rangle_4)$$

Four Bell states

$$|\Psi^{\pm}\rangle_{23} = \frac{1}{\sqrt{2}}(|H\rangle_2|V\rangle_3 \pm |V\rangle_2|H\rangle_3)$$

$$|\Phi^{\pm}\rangle_{23} = \frac{1}{\sqrt{2}}(|H\rangle_2|H\rangle_3 \pm |V\rangle_2|V\rangle_3)$$

State of this system

$$\begin{aligned}|\Psi\rangle_{1234} &= \frac{1}{2}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2) \\ &\quad \otimes(|H\rangle_3|V\rangle_4 - |V\rangle_3|H\rangle_4) \\ &= \frac{1}{2}(|\Psi^+\rangle_{14}|\Psi^+\rangle_{23} + |\Psi^-\rangle_{14}|\Psi^-\rangle_{23} \\ &\quad + |\Phi^+\rangle_{14}|\Phi^+\rangle_{23} + |\Phi^-\rangle_{14}|\Phi^-\rangle_{23})\end{aligned}$$

Żukowski M et al., Phys. Rev. Lett. 1993, 71(26): 4287–4290; J.-W. Pan et al., Phys. Rev. Lett. 1998, 80(18): 3891–3894.

A brief review on Entanglement swapping

Applications

① Physics foundations

nonlocality , wave–particle duality, …
(A. Peres, 2000; C. Branciard et al., 2010 …)

② Quantum networks

Quantum repeater, Quantum relay, Quantum key distribution, …
(H. J. Briegel et al., 1998; L. M. Duan et al., 2001; Q.-C. Sun et al., 2017 …)

Requirements

① Independent quantum sources

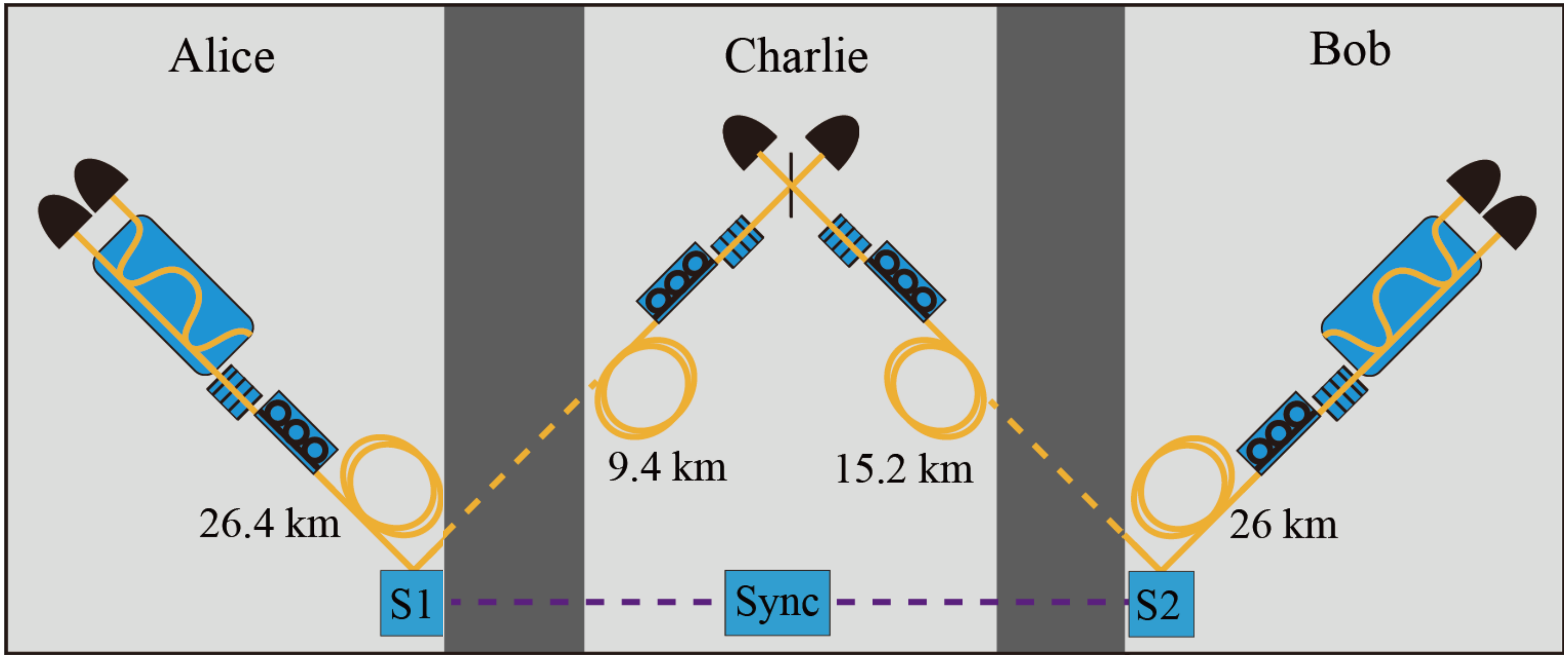
② Field test

T. Yang et al., Phys.Rev.Lett., 2006
M. Halder et al., 2007
R. Kaltenbaek et al., 2009
B. Hensen et al., Nature, 2015 (1.3 km)
R. Valivarthi et al., Nat. Photon., 2016 (17 km)
Q.-C. Sun et al., Nat. Photon., 2016 (25 km)
…

Outline

② Entanglement swapping over 100 km optical fiber

Schematic diagram



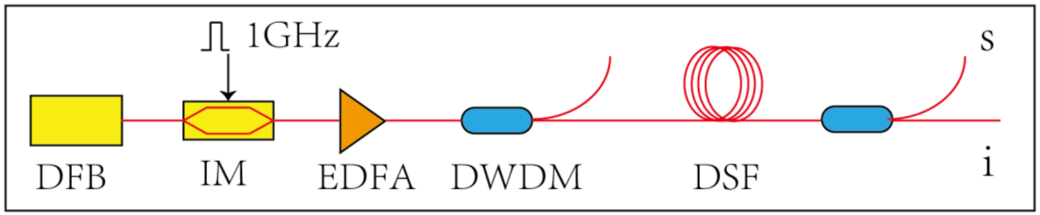
Alice	Innovation Ind. Park	Prepares& distributes EPR pairs, Performs state analysis
Charlie	Software Park	BSM
Bob	USTC	Prepares& distributes EPR pairs, Performs state analysis

Technical challenges:

- Interference between independent photons (Indistinguishability of photons)
- Transmission loss
- Stability of system and channel

Map data: Google. CNES/Astrium. DigitalGlobe.

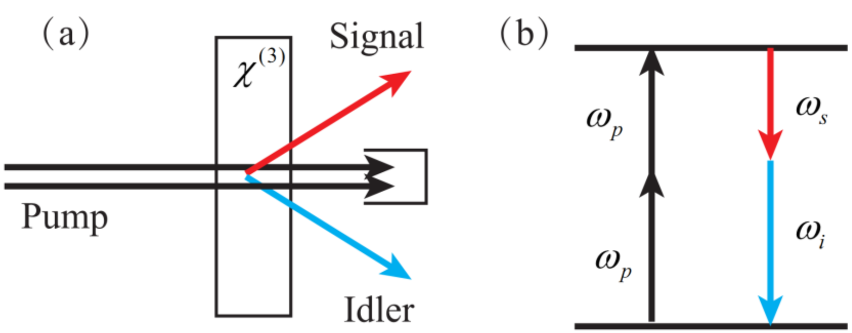
Sequential time-bin photon pairs source



- Repetition rate
  1 GHz
- Pulse duration
  75 ps
- Extinction ratio
  > 26dB

$$|\Phi\rangle = \frac{1}{\sqrt{n}} \sum_{k=0}^{n-1} e^{ik\theta} |t_k\rangle_s |t_k\rangle_i$$

Spontaneous four-wave-mixing in dispersion shifted fibre:



Frequency correlation:

$$|\Psi_2\rangle = \int d\omega \psi(\omega) |\omega\rangle |2\omega_p - \omega\rangle$$

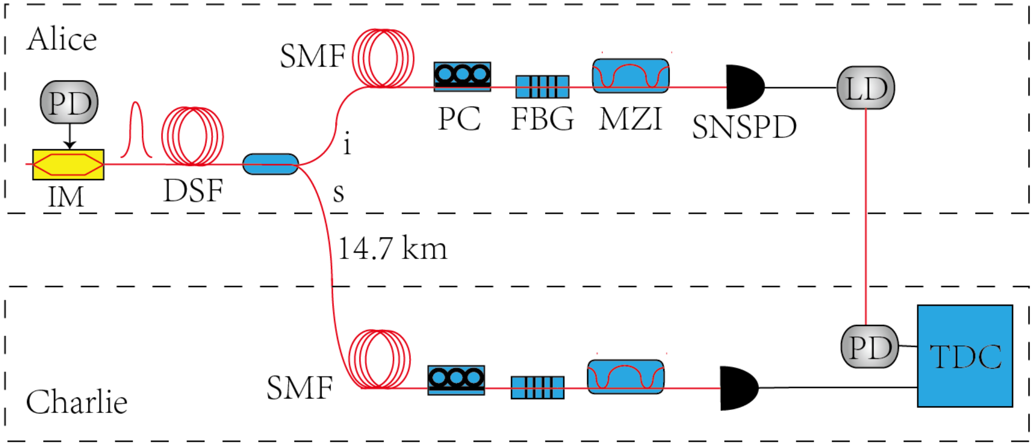
$$\sigma_s(\sigma_i) \approx 4GHz$$

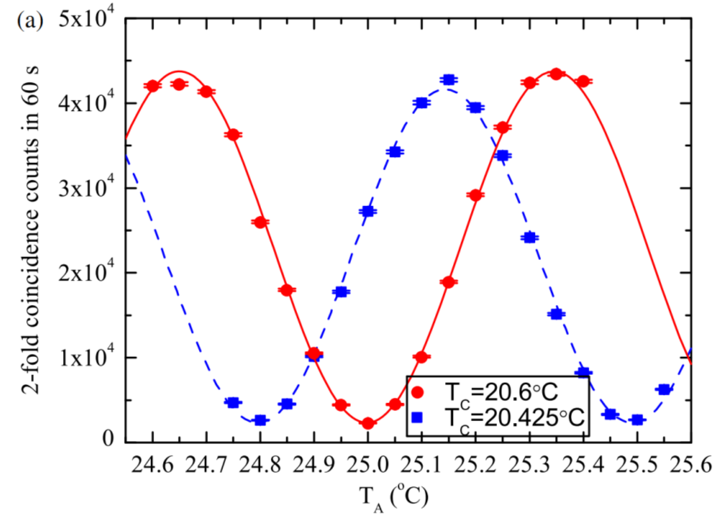
$$\sigma_p \approx 7GHz$$

$$V > 99\%$$

Zhou et al. Phys. Lett. A 375 2274 (2011); Żukowski et al. Ann. N. Y. Acad. Sci, 755 91-102 (1995); Q. Zhang et al. Opt. Express 16, 3293–329 8 (2008).

Sequential time-bin photon pairs source

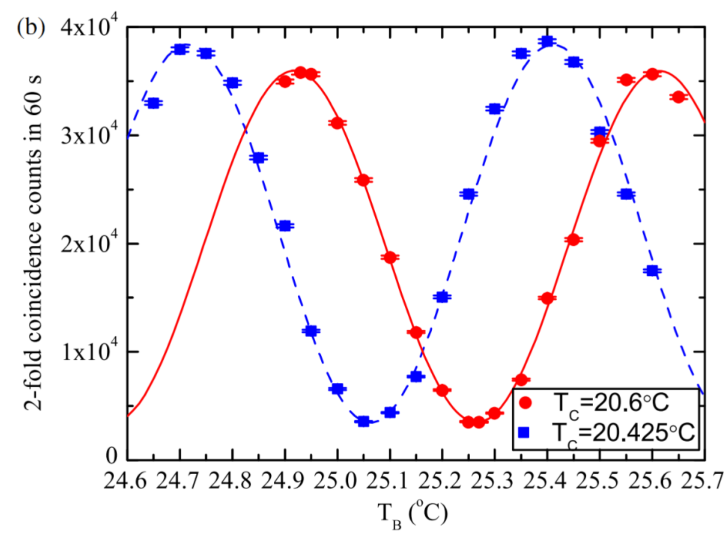




The visibility of the fitted curve:

(a) Alice: **(89.8 ± 0.5)%**

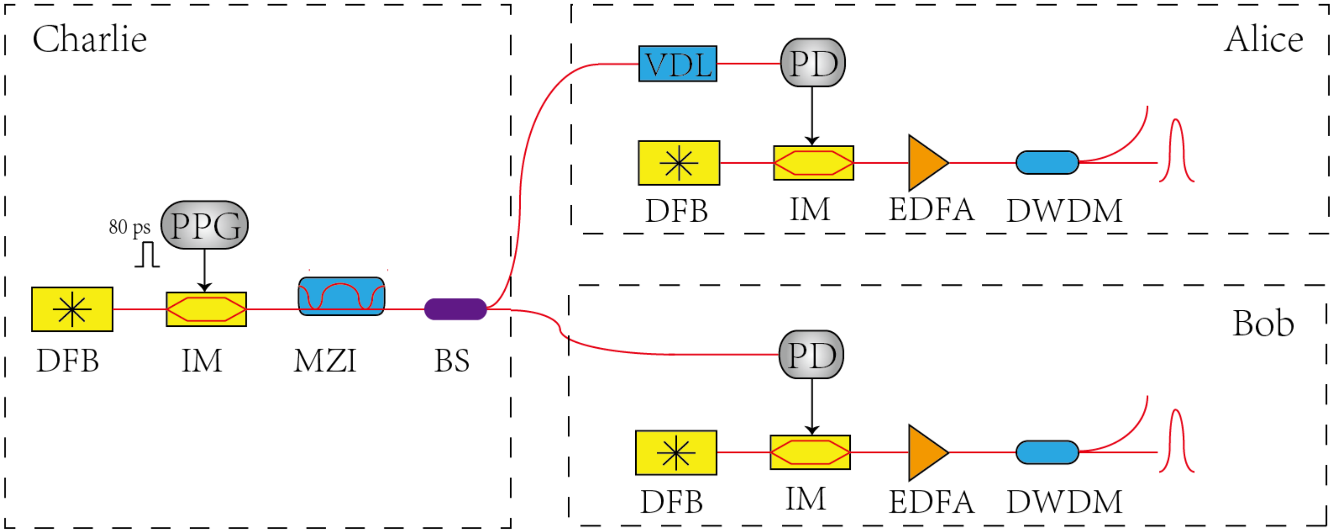
(b) Bob: **(82.9 ± 1.2)%**



- Multi pair events and the noise (~93%)
- Temperature fluctuation (~96%)
- Limited bandwidth of the photodiode.

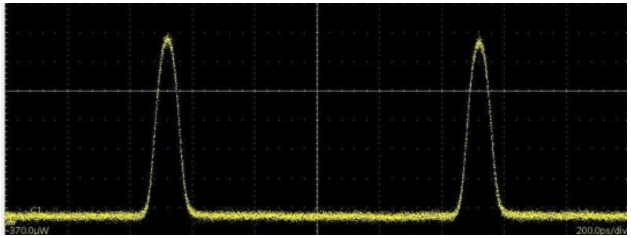
Q. Zhang et al. Opt. Express 16, 3293–3298 (2008).

Synchronization of independent sources



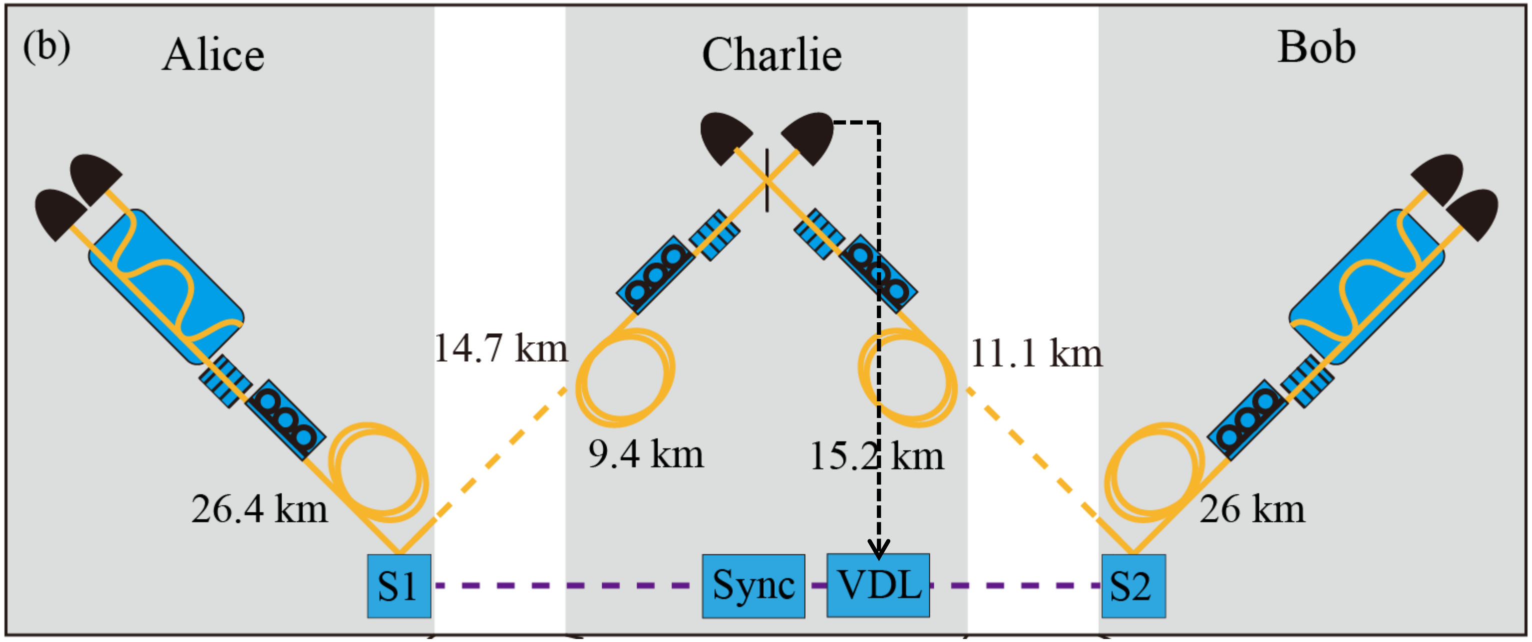
RMS time jitter

$$\sigma_t = \sqrt{\sigma_{t1} + \sigma_{t2}} \approx 2.04 \text{ ps}$$



Which are much smaller than the coherent time of the signal photons (~ 110 ps).

System stabilization



Automatic stabilization:

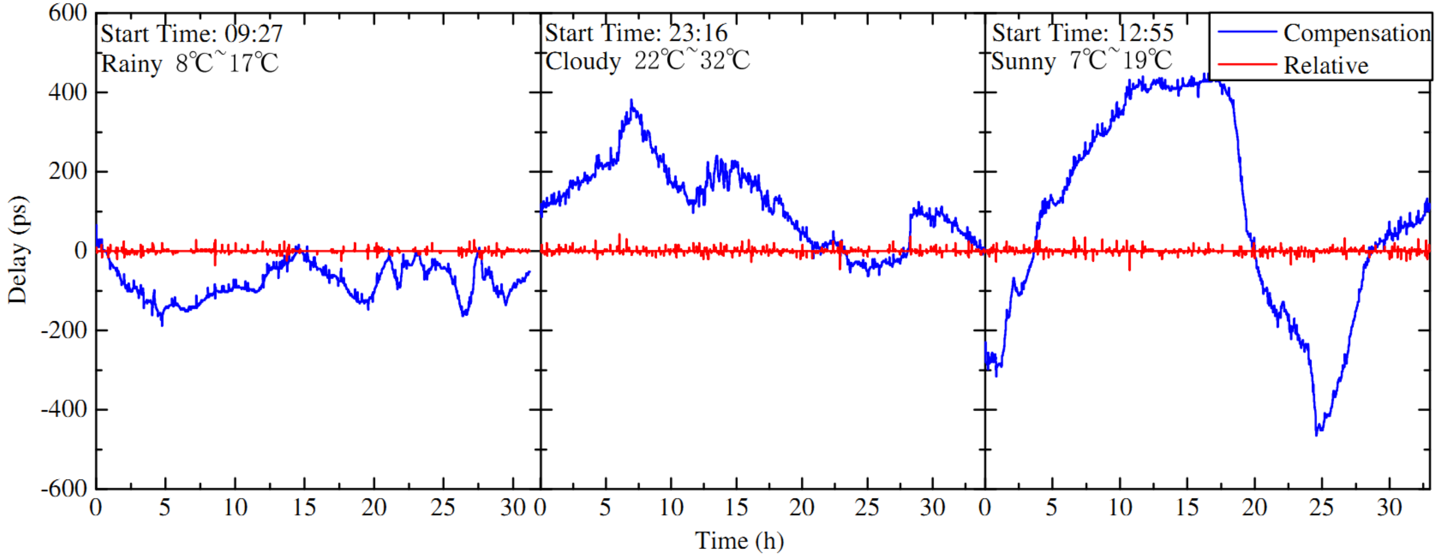
- Time delay
- Polarization
- MZI, FBG, EOM, Pump power

...

Measure the difference between the arrival time of the signal photons from Alice and Bob as error signals and feed them into delay lines.

- Measured by a TDC with time resolution of 4 ps
- Feedback interval time: 100 s

System stabilization



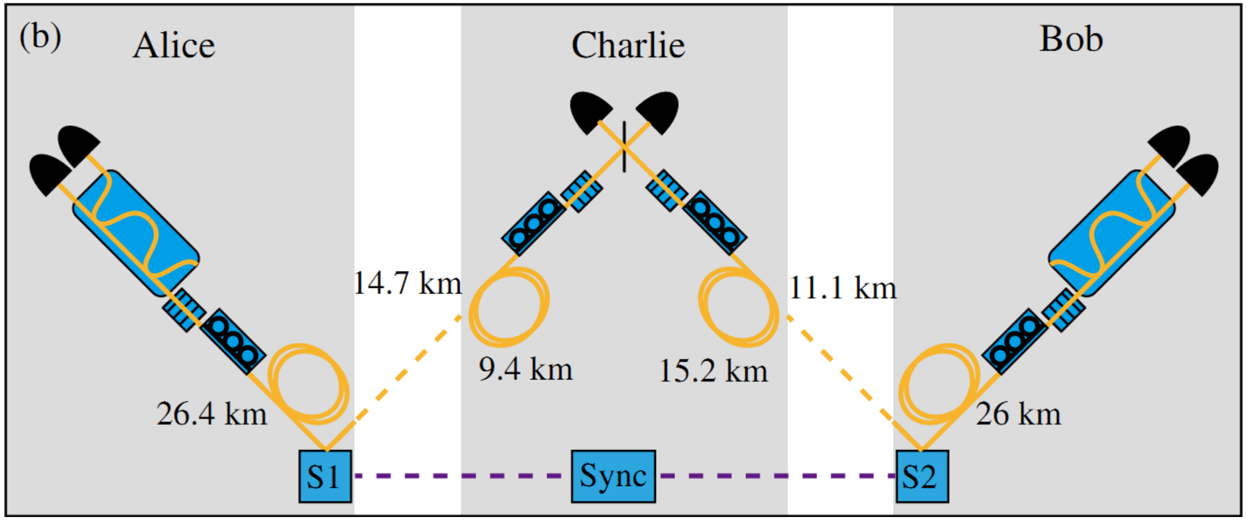
The standard deviations of the relative delay:

(a) : Rainy **6.7 ps**, (b) : Cloudy **6.0 ps**, (c) : Sunny **6.5 ps**.

Which are much smaller than the coherent time of the signal photons (~ 110 ps).

Our system can work well in different weather conditions.

Experimental results

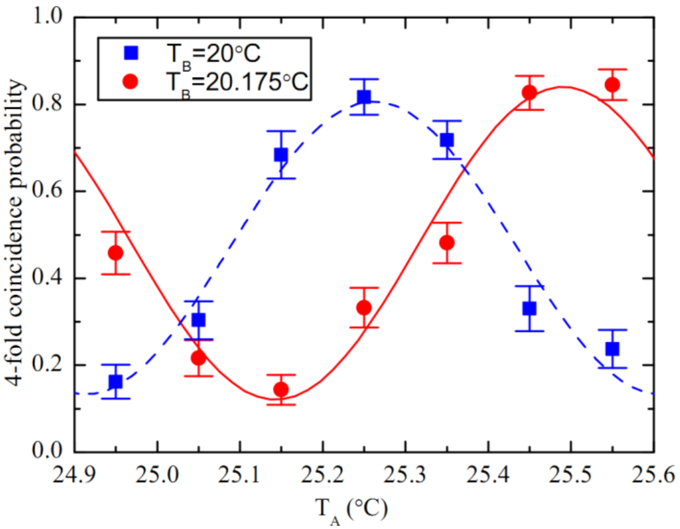


BSM:

$$|\Psi^-\rangle_k = \frac{1}{\sqrt{2}}(|t_k\rangle|t_{k+1}\rangle \pm |t_{k+1}\rangle|t_k\rangle)$$

Created entanglement state:

$$|\Psi^-\rangle_k = \frac{1}{\sqrt{2}}(|t_k\rangle|t_{k+1}\rangle \pm |t_{k+1}\rangle|t_k\rangle)$$



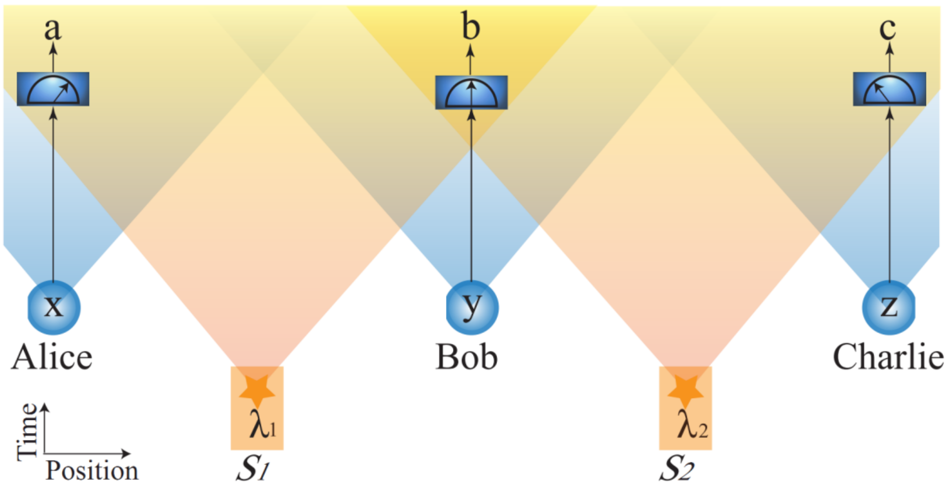
- Each data point is accumulated for more than 30 h
- The average visibility is (73.2 ± 5.6)%

Classical limit 1/3

Outline

③ Experimental demonstration of nonbilocality

Experimental demonstration of nonbilocality



$$\mathcal{B} = \sqrt{|I|} + \sqrt{|J|} \leq 1$$

$$I = \frac{1}{4} \sum_{x,z} \langle A_x B_0 C_z \rangle$$

$$J = \frac{1}{4} \sum_{x,z} (-1)^{x+z} \langle A_x B_1 C_z \rangle$$

Models where independent systems are characterized by different, uncorrelated hidden states λ .

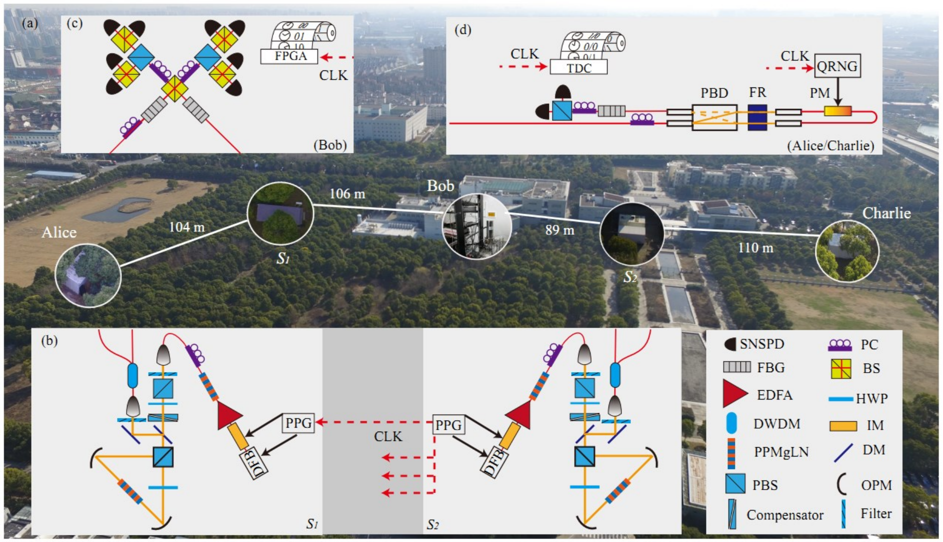
$$P(a,b,c|x,y,z) = \iint d\lambda_1 d\lambda_2 \, \rho_1(\lambda_1) \, \rho_2(\lambda_2) \times P(a|x,\lambda_1) P(b|y,\lambda_1,\lambda_2) P(c|z,\lambda_2)$$

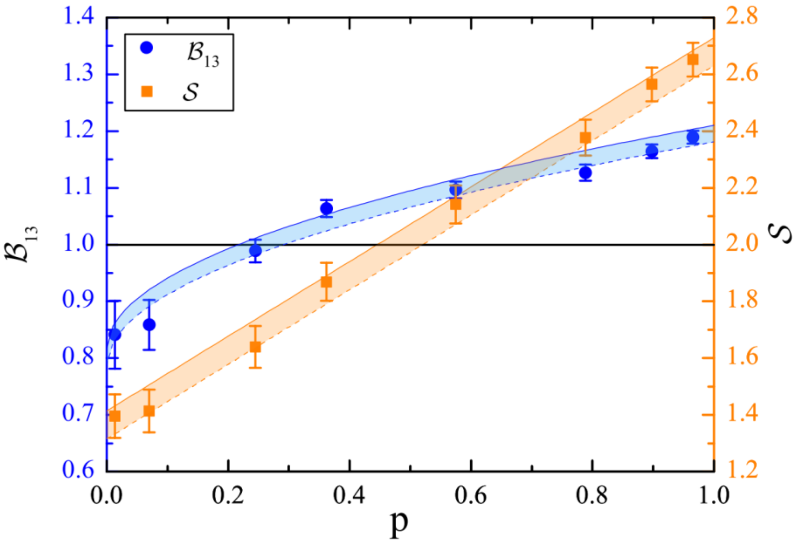
$$V_{biloc} > 50\%$$

$$V_{CHSH} > 1/\sqrt{2} \approx 70.7\%$$

C. Branciard, N. Gisin,and S. Pironio, PRL 104, 170401 (2010)

Experimental demonstration of nonbilocality





- True Independent source
- Strict locality constraint
- Measurement independence

p: the noise parameter

Result:

$$B = 1.181 \pm 0.004 > 1$$

$$S_{CHSH} = 2.652 \pm 0.059 > 2$$

arXiv: 1807.05375

This work is subject to press embargo!

Outline

④ Summary and outlook

Summary and outlook

The first experiment

- Our experiment has shown that realizing entanglement swapping between two cities is technically feasible:

The Second experiment

- Our experimental realization constitutes a fundamental block for a large quantum network.
    - True Independent source
    - Strict locality constraint
    - Measurement independence

Outlook：

- Test the fundamental issues of quantum information science
- Stimulate novel information processing applications
- Quantum networks with multi-sources, free-space channel, etc.

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Thank you for your attention!