Joint Spectral Intensity Measurement of Time-frequency Entangled Photon Pair with High-resolution Time-of-Flight Spectrometer

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Abstract

Pairs of photons entangled in the time-frequency mode (TFM) play a significant role in quantum communication due to their high information capacity and adaptability in fiber networks. To further advance the application of TFM quantum information in quantum technology, a crucial technical task is the reconstruction of TFM quantum information, including the joint spectral intensity (JSI) of entangled photon pairs. In this work, we developed a fiber-based time-of-flight spectrometer (ToFS) using a single photon detector and an optical fiber to introduce group delay dispersion (GDD). This ToFS utilizes the frequency-to-time mapping technique to convert the frequency information of single photons into arrival time at the single photon detector, thereby reconstructing the frequency distribution of single photons in this compact experimental setup. To demonstrate the performance of our developed ToFS, we used it to experimentally measure the JSI of telecom C-band photon pairs generated through spontaneous parametric down-conversion (SPDC). Our results indicate that the developed ToFS efficiently captures the frequency correlation of photon pairs, with a wavelength resolution estimated at 2.5 nm. This work showcases a critical technique for measuring TFM quantum information. We believe this technique holds immense potential for applications in quantum technology, including TMF quantum key distribution, high-dimensional TMF quantum computing, and quantum sensing.

Introduction

- Photons is a suitable carrier for quantum information science (QIS) because of the characteristics of weakly interacting with themselves and environment. [1]
- The nature of SPDC can easily generate photon pairs with high correlation and quantum entanglement which is a suitable quantum source for quantum communication.
- Time-frequency mode is a degree of freedom insensitive to medium perturbations and compatible with existing single-mode fiber networks.

Theoretical Model

- Spontaneous Parametric Down-Conversion (SPDC): | A nonlinear optical process that converts a higher energy pump photon into a pair of photons with lower energy, in accordance with the law of **energy** and **momentum conservation** during production (Fig.1).
- Quantum state of SPDC: $|\psi\rangle = \int\int f(\omega_s,\omega_i) a^\dagger_{\omega_s} a^\dagger_{\omega_i} |0\rangle_s |0\rangle_i d\omega_s d\omega_i$, where $f(\omega_s,\omega_i)$ is the Joint spectral amplitude (JSA) , which record the frequency correlation between photons. $a^\dagger_{\omega_s}|0\rangle_s$ denotes the single-photon state at frequency ω_s.
- Characterizing Joint Spectral Amplitude (JSA): | Corresponding to the amplitude of probability of measuring one of photon pair at ω_s (called the signal) and the other one at ω_i (called idler) as Fig.2 shown, JSA can be factorized as pump spectrum and phase-matching function, .

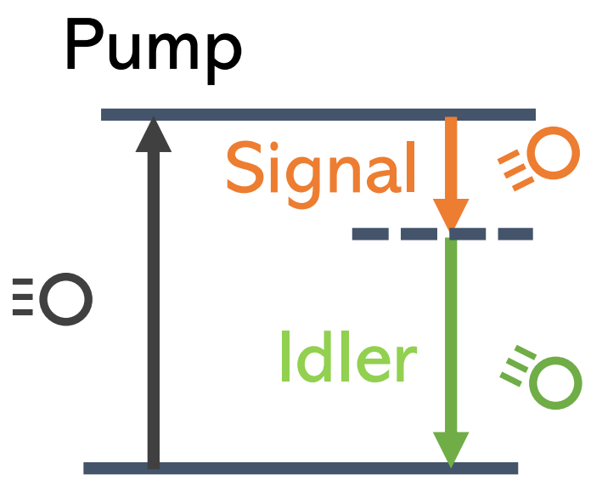


Fig. 1 Schematic of SPDC process

Pump spectral function: $\Phi_p(\lambda_s,\lambda_i) = \exp\left[-\frac{(c/\lambda_s + c/\lambda_i - c/\lambda_p)^2}{4B_p^2}\right]$, where B_p is the pump linewidth.

Phase-matching function: $\Phi_{PMC}(\lambda_s,\lambda_i) = \text{sinc}(\frac{\Delta kL}{2})$, where $\Delta k = k_p(\lambda_p) - k_s(\lambda_s) - k_i(\lambda_i)$.

$$f(\omega_s,\omega_i) = \begin{matrix}\Phi_p(\lambda_s,\lambda_i)\\ \times \\ \Phi_{PMC}(\lambda_s,\lambda_i)\end{matrix}$$

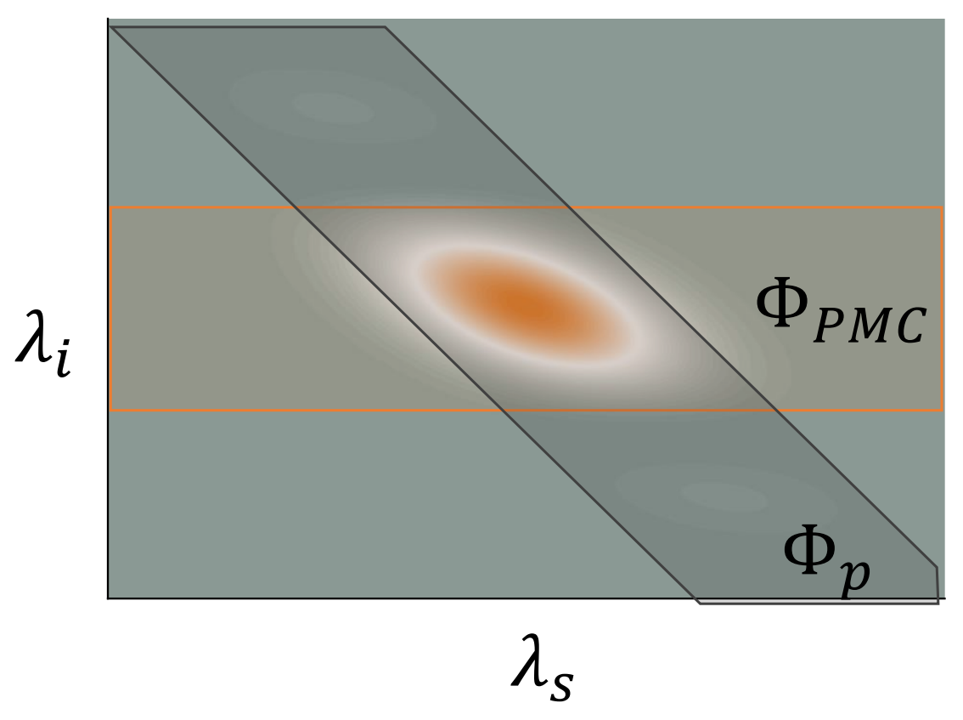


Fig.2 Relation between Φ_p, Φ_{PMC} and f

- Schmidt decomposition [2]: | To understand the entanglement degree from JSI, and which is the absolute square of JSA, Schmidt decomposition can help us decompose the JSI of several orthogonal frequency modes. The more factorized modes are, the entanglement degree is higher, which is defined by Schmidt number K.

Schmidt decomposition:

$$f(\omega_s,\omega_i) = \sum \sqrt{\beta_i}\, u_k(\omega_s) \otimes v_k(\omega_i)$$

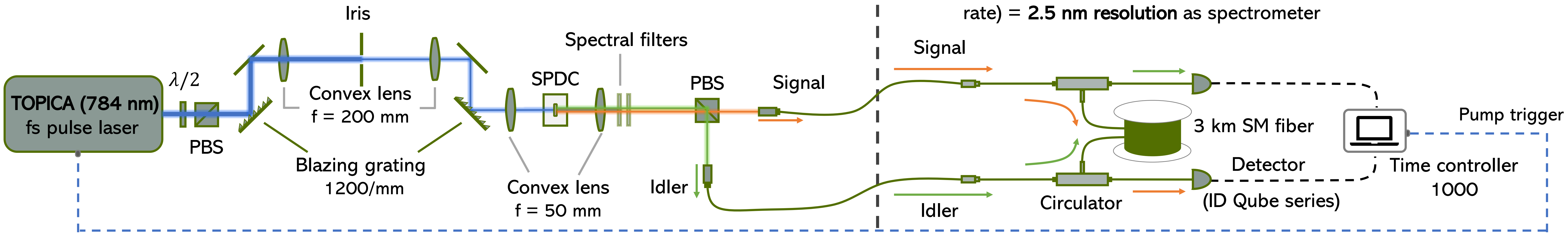
Schmidt number:

$$K = \frac{1}{\sum \beta_i^2}$$

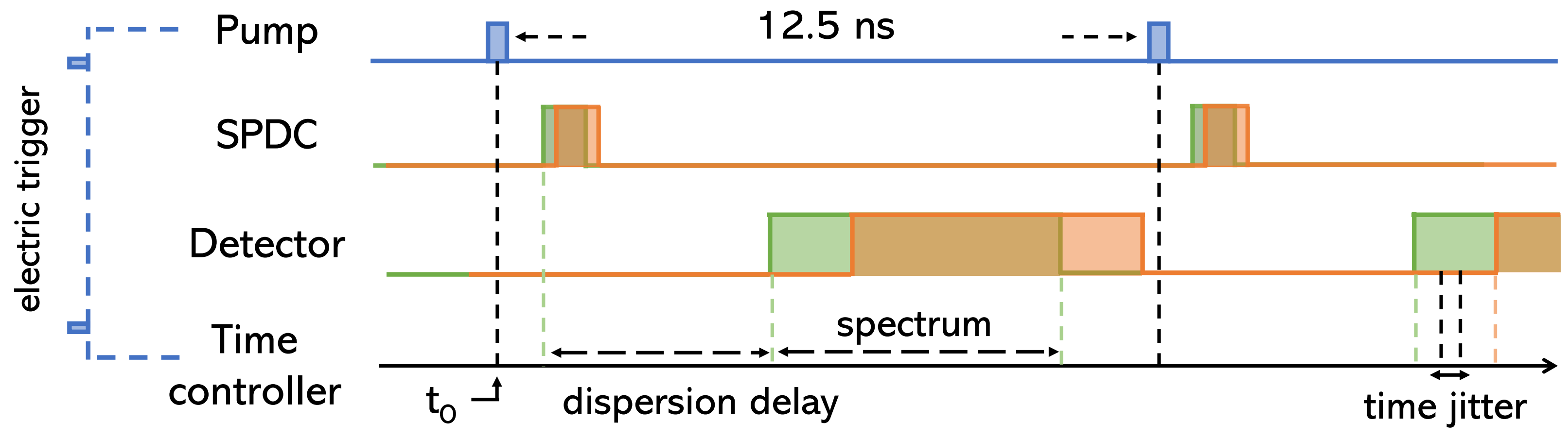
- Correlation between pump bandwidth and entanglement (Schmidt number)
- Entanglement manipulation by pump bandwidth

Experimental Setup

- Pulse-pump SPDC source:
  - Pump with 100 fs pump pulse duration to define the zero-delay time
  - Type-II SPDC with1 mm crystal length PPLN
- Fiber-based time-of-flight spectrometer (ToFS)
  - 150 ps (time jitter) / 3 km (fiber length) x 20 ps/km/nm (dispersion rate) = **2.5 nm resolution** as spectrometer



- Time sequence and data analysis:



Photon pair generation ⇨ Fiber Dispersion ⇨ Detector receive idler and signal photon ⇨ Preserve the signal from the same pulse ⇨ Record the delay with trigger ⇨ Mapping on JSI

Experimental Results

- Measurement of SPDC JSI by ToFS

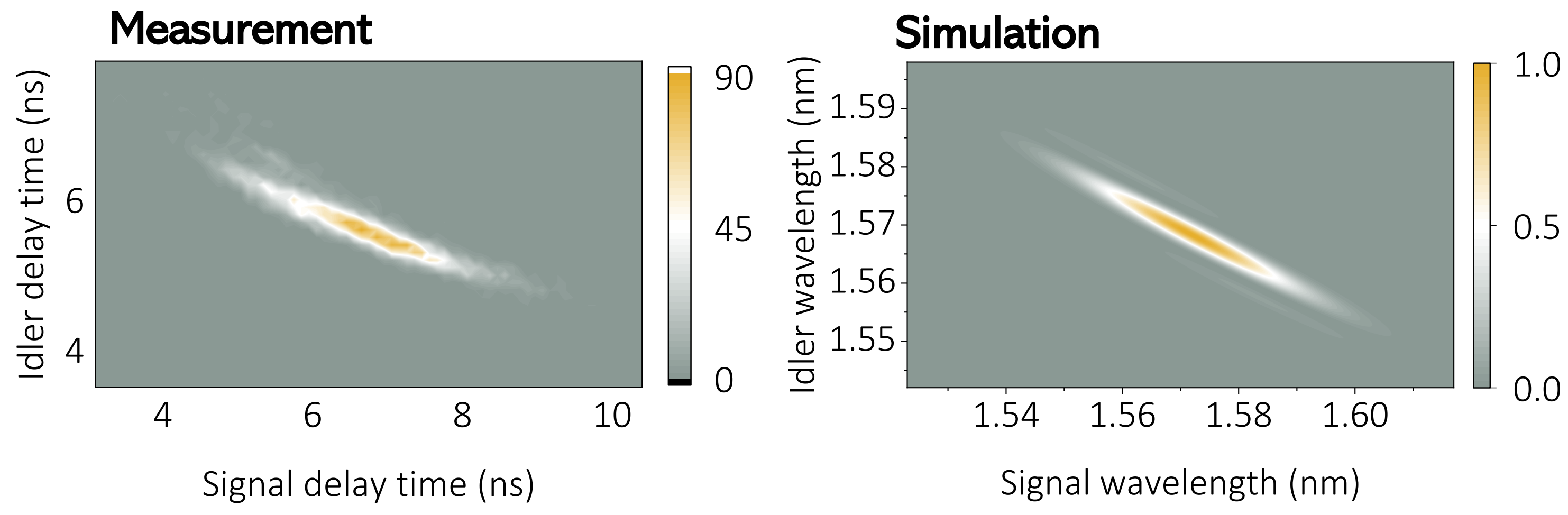
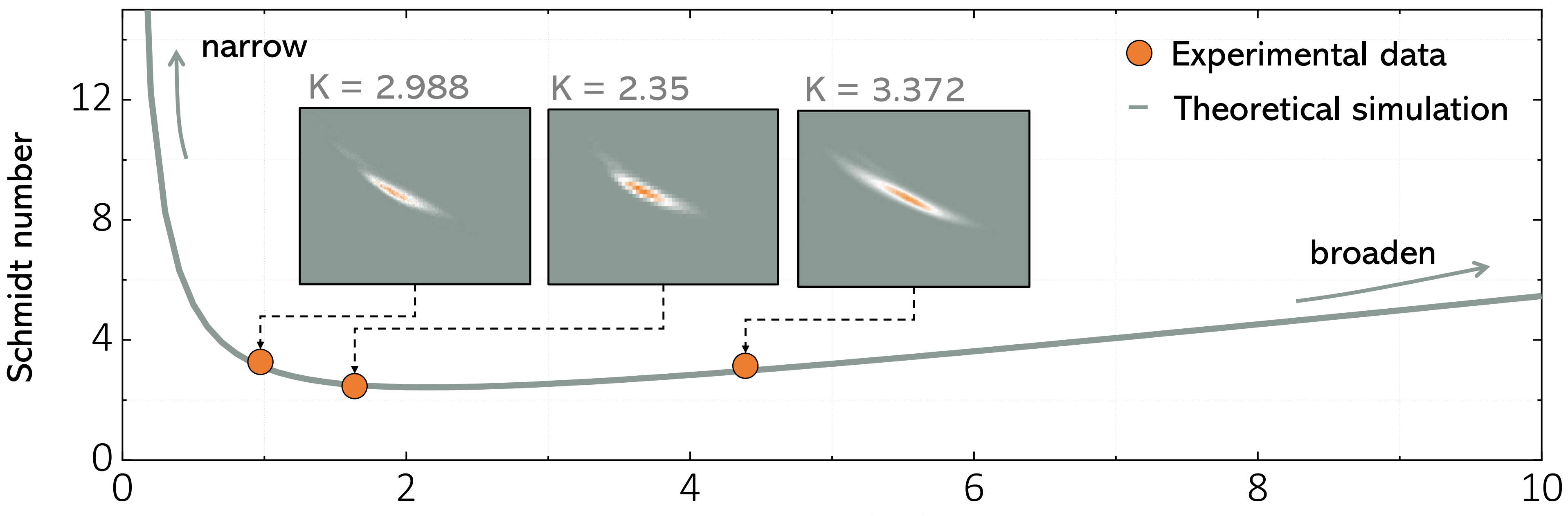


Fig.3 Comparison between measurement and simulation JSIs. The accumulation time (resolution) of experiment is 30 mins (100 ps/pixel).

- Entanglement manipulation | The pump bandwidth can affect the shape of JSI, and also affect the entanglement degree (Schmidt number).



Conclusion

The experiment provides a convenient method to measure the JSI and directly verify the photon pair correlation, which can analyze and decode the information from single photons for TMF QIS and quantum communication.

Reference

[1] Brecht, B. , et al. (2015). Photon temporal modes: a complete framework for quantum information science. Physical Review X, 5(4), 041017.
[2] Li, B., et al. (2023). Pure-state photon-pair source with a long coherence time for large-scale quantum information processing. Physical Review Applied, 19(6), 064083.
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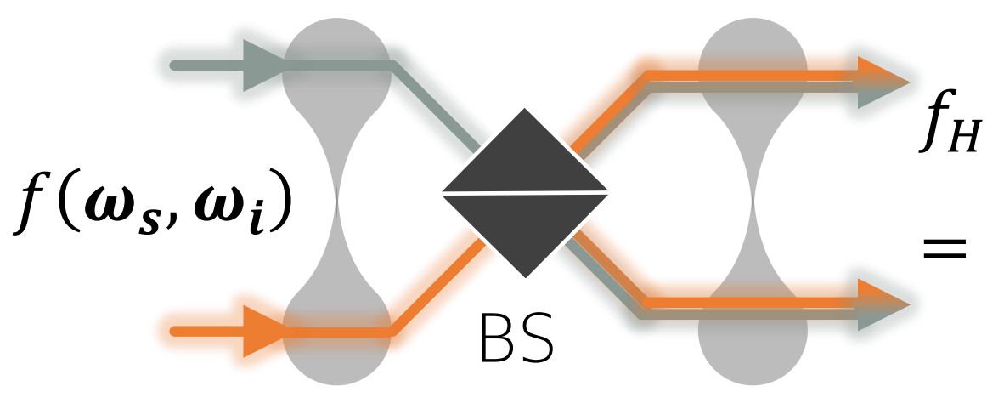
Future work

- Dispersion frequency calibration
- HOM interference: Quantum interference between two symmetry JSIs.

$$|\psi\rangle_{SPDC} \Rightarrow |\psi\rangle_{HOM} = \int\int d\omega_s d\omega_i f_{HOM}(\boldsymbol{\omega_s},\boldsymbol{\omega_i})|\omega_s\rangle|\omega_i\rangle$$



$$f_{HOM}(\boldsymbol{\omega_s},\boldsymbol{\omega_i}) = f(\boldsymbol{\omega_s},\boldsymbol{\omega_i})e^{-i(\omega_s-\omega_i)\tau} - f(\boldsymbol{\omega_i},\boldsymbol{\omega_s})$$

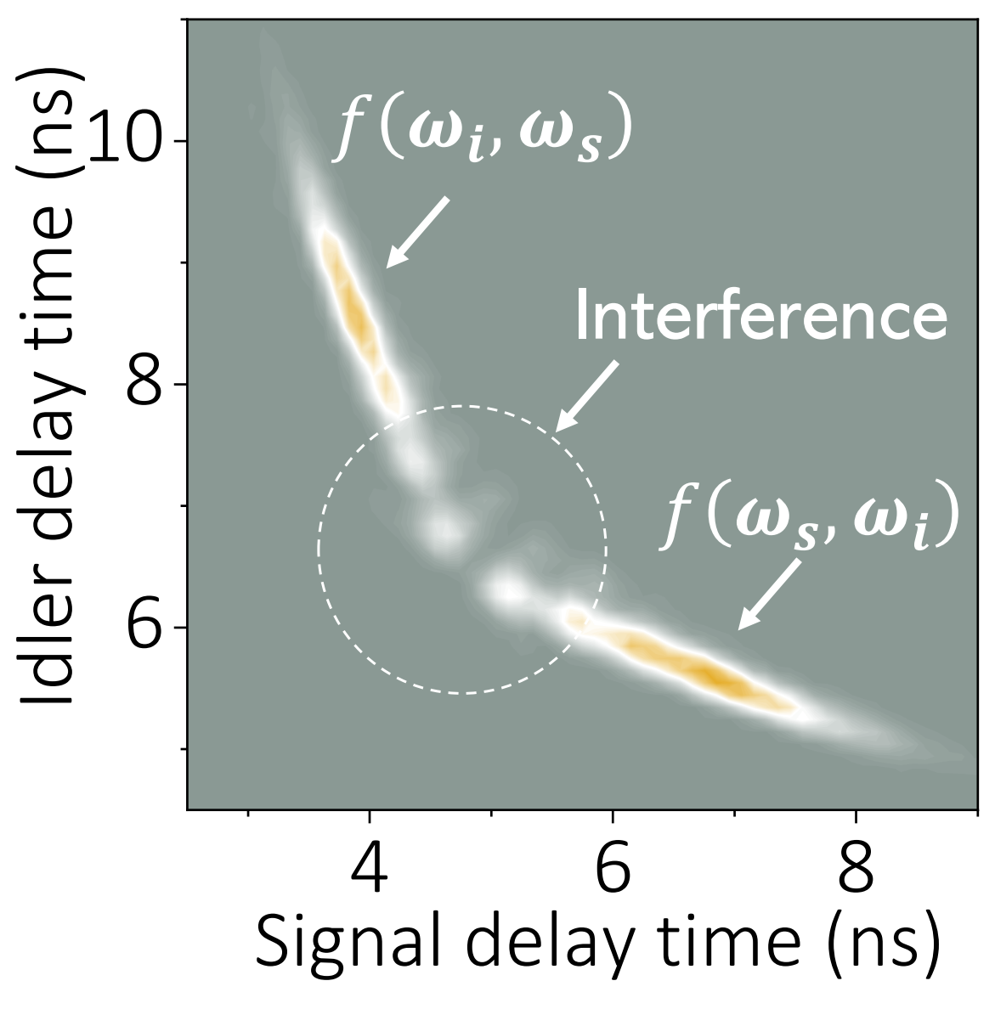


Fig.4 The measured with HOM JSI. The accumulation time is 10 hrs.