Quantum State Tomography of Photonic Frequency-Encoded States via Hong-Ou-Mandel Interference

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The frequency degree of freedom of photons enables the generation of high-dimensional quantum states within a single spatial mode and is expected to be useful to quantum information processing. However, conventional quantum state tomography (QST) of the frequency-encoded photonic quantum state suffers from losses associated with the frequency conversion, which are required to change the measurement basis. To overcome this issue, QST using Hong-Ou-Mandel (HOM) interference (HOM-QST) was proposed. In this scheme, the operations applied to the signal photons are limited to the transmission of a passive beamsplitter, while the required control is implemented to the probe light [1]. Here we apply the HOM-QST to frequency-encoded states. From HOM interference patterns between the signal and probe light for various probe states, we successfully reconstructed the density matrix of the frequency-encoded signal state.

Figure 1 shows the experimental setup. Arbitrary frequency-bin states are independently encoded onto the signal and probe modes using WaveShapers (Coherent, Inc.), where both modes are weak coherent states obtained from broadband optical pulses. The center frequencies of the Gaussian-shaped frequency basis are 193.13 ($|f_1\rangle$) and 193.28 ($|f_2\rangle$) THz with the bandwidths of 44 GHz. A relative phase between the signal and probe light is randomized by using a phase shifter inserted in the signal arm. The signal and probe pulses are subsequently combined at a 50/50 beamsplitter. By measuring the coincidence counts between the two output ports of the beamsplitter while sweeping the probe delay time, we obtain the HOM interference pattern. We can obtain the element $\langle k|\rho|k\rangle$ of the signal's density matrix ρ from the HOM dip depth Δ_k, where $|k\rangle$ is the probe state [1]. From Δ_k for various $|k\rangle$, we estimate the density matrix of the signal state with the diluted maximum likelihood method.

We successfully reconstructed the density matrices (Fig. 2) of the various states of signal light, including the six Pauli eigenstates spanned by $|f_1\rangle$ and $|f_2\rangle$ basis. We obtained the average fidelity to the target states to be 0.996 ± 0.007, demonstrating the validity of HOM-QST for the frequency-encoded states. Future work includes performing HOM-QST on single-photon frequency qubits, frequency-entangled states, and even higher-dimensional frequency superposition states.

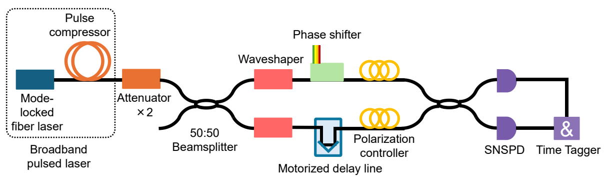

Fig. 1: *Experimental setup.*

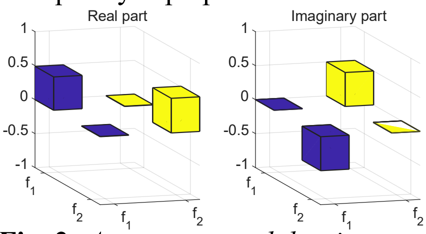

Fig. 2: *A reconstructed density matrix ($(|f_1\rangle - i|f_2\rangle)/\sqrt{2}$ state).*

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References

[1] Y. Tsujimoto *et al.*, Phys. Rev. Appl. **19**, 014008 (2023).