Photon states encoded in polarization and picosecond time-bins

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We introduce a two-qubit and a qubit-qutrit information system, realized by two degrees of freedom in a single photon: polarization and picosecond time-bin. We demonstrate the reconstruction of these states with information encoded in a photon using quantum state tomography.

As one of the most successful realizations of quantum bits, photons are widely used as the source in experimental demonstrations of quantum information. While usually the photon polarization degree of freedom is used to encode the quantum information, other degrees of freedom (DOF) are available as possible realization of qubits as well. Moreover photons' DOFs are not restricted to realize two-level system, but also a d-level system represented by a qudit.

Since the BB84 paper [1], concerning with the states needed for secure quantum key distribution, mutually unbiased (MUB) bases offer the most efficient defense against an eavesdropper attack. These MUB bases are more efficient in other quantum protocols such as quantum state tomography [2]. A Hilbert space of dimension D is known to have $D+1$ MUB bases, where D is a prime number or the power of a prime number. The number of MUB bases of a Hilbert space of a different dimension D, still remains an open problem. Currently, for the simplest case $D = 2\otimes 3$, only 3 MUB bases were found with no proof noting the predicted number [3].

In this work we present and demonstrate a scheme which is able to encode a qubit-qudit state in one photon, using two of its degrees of freedom - polarization and time. Our scheme is simple - does not require delay loops - and we present a method of measurement. The polarization degree of freedom represents the logical qubit with the horizontal (vertical) h (v) polarizations. The time degree of freedom is the photon arrival time to a beamsplitter, which is divided into time-bins, and any superposition of them is possible. We define the logical qudits as $0/\tau/2\tau/../(d-1)\tau$ time delays, realized by passing the photon through $d-1$ birefringent crystals for $d\tau$ time-bins. The temporal state $|0\rangle$ is defined as the time it takes for the extraordinary ray to reach the beamsplitter, and $|\tau\rangle$ as it takes the ordinary one. While τ is approximately 2 pico-seconds, arrival detection time is possible by using an ancilla photon and projetion on a beamsplitter.

Using linear optical elements we are able to create and reconstruct various states. In Fig. 1 the reconstructed density matrices of $2\otimes 2$ and $2\otimes 3$ states are presented with fidelities of 98% and 95% to the desired state.

While this work presented 3 time-bins, more could be added by adding birefringent crystals. In order to maintain scalability the birefringent crystals could be replaced by integrated waveguides and the beamsplitter could be replaced by a standard fiber coupler.

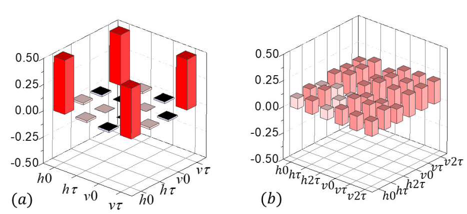

Figure 1: Reconstructed density matrix (a) $\frac{1}{\sqrt{2}}(|h,0\rangle + |v,\tau\rangle)$ (b) $\frac{1}{\sqrt{2}}(|h\rangle + |v\rangle)\otimes\frac{1}{\sqrt{3}}(|0\rangle + |\tau\rangle + |2\tau\rangle)$

References

[1] C. H. Bennett, G. Brassard, in *Proceedings of IEEE International Conference on Computers, Systems and Signal Processing*, 175 (1984).

[2] D. F. V. James, et. al., "Measurement of qubits", Phys. Rev. A. **64**, 052312 (2001).

[3] V. D'Ambrosio, et. al.,"Test of mutually unbiased bases for six-dimensional photonic quantum systems", Sci. Rep. bf 3, (2013)