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Tomography of a Feedback Measurement with Photon Detection

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Measurement and discrimination of quantum states are essential tasks in quantum information processing. A measurement strategy consisting of photon detection preceded by a displacement operation, that is actively feedback-controlled depending on the photon detection outcomes, is known to be a powerful measurement technique for quantum state discrimination [1]. In our work, we experimentally develop such a feedback measurement with photon detection and characterize its positive operator valued measure (POVM) via quantum detector tomography using coherent states. Quantum detector tomography has been demonstrated for various types of static measurements [3], but not before for a dynamically updated measurement. As a potential application of the feedback measurement for quantum state discrimination, we analyze the performance of our measurement for the discrimination of the two orthogonal superpositions of vacuum and single photon states $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$, which are the conjugate basis states of the optical single-rail qubit.

A schematic of the feedback measurement is shown in Fig.1(a). It consists of a displacement operation, a single photon detector and real time feedback control of the displacement phase and amplitude dependent on outcomes from the single photon detector. An incoming quantum state $|\psi\rangle$ with the full time width T is virtually divided into M temporal mode bins with time width t_i for the i th mode. The displacement operation for each time mode bin is determined based on the counting history of preceding photon detections performed on earlier time bins. By performing an infinitely fast control of the displacement operation ($M \rightarrow \infty$), the two orthogonal superpositions can be perfectly discriminated without error [2].

Experimental results of the estimated error probability for the feedback measurement $M = 2$ with various setting of t_1 are shown in Fig.1(b). Red dots are the error probabilities experimentally estimated from the reconstructed POVM of the feedback measurement. Red (Blue) solid and dotted lines respectively represent the theoretical values of the feedback measurement with $M = 2$ and $M = 1$ in the experimental (ideal) condition with a 98% (100%) visibility of the displacement operation. By optimizing the timing of performing the feedback operation, we observe a clear improvement of the error probability over a static strategy without feedback control of the displacement ($M = 1$). Furthermore, we perform the quantum detector tomography on the feedback measurement with various number of feedback steps $M = 3 - 5$. The experimentally estimated error probabilities are plotted in Fig.1(c). Our experimental results indicate that the discrimination error can be improved by increasing the number of feedback operation and our feedback measurement would be a beneficial tool for various applications using the single-rail optical qubit [4].

Fig. 1 (a) Schematic of the displacement followed by single photon counter (SPC) with feedback operations. Estimated error probabilities for the discrimination of the superposition states with the feedback measurement (b) $M = 2$ and (c) $M = 1 - 5$.

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