Continuous-variable quantum process tomography with squeezed-state probes

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We propose a procedure for tomographic characterization of continuous variable quantum operations which employs homodyne detection and single-mode squeezed probe states with a fixed degree of squeezing and anti-squeezing and a variable displacement and orientation of squeezing ellipse. Density matrix elements of a quantum process matrix in Fock basis can be estimated by averaging well behaved pattern functions over the homodyne data. We show that this approach can be straightforwardly extended to characterization of quantum measurement devices. The probe states can be conveniently measured with homodyne detectors [6, 8]. Recently, this approach has been successfully employed to characterize a single-mode lossy channel [27], and a conditional single-photon addition and subtraction [30]. Moreover, the coherent states were also used as probes for complete tomographic characterization of single-photon detectors [31, 33]. Probing quantum processes with coherent states essentially amounts to determining a Husimi Q-function of the operator χ. More precisely, assuming that the measurements on output states are described by a POVM with elements Πj, the probability of measurement outcome Πj for input probe coherent state |α⟩ reads

\[ p_j(\alpha) = \text{Tr}[|\alpha|^*|\alpha| \otimes \Pi_j]. \]

Usually, one would like to reconstruct the matrix elements of χ in Fock basis. To see the connection between the Husimi Q-function and the matrix elements in Fock basis, recall that the Q-function of an operator A is defined as

\[ Q(\alpha, \alpha^*) = \frac{e^{-|\alpha|^2}}{\pi} \sum_{m,n=0}^{\infty} \frac{\alpha^* m \alpha n}{\sqrt{m! n!}} A_{m,n}, \]

which shows that the Q-function is a generating function of matrix elements \( A_{m,n} = \langle m|A|n\rangle \) in Fock basis [28].

\[ A_{m,n} = \frac{\pi}{\sqrt{m! n!}} \frac{\partial^{m+n}}{\partial \alpha^m \partial \alpha^n} [Q(\alpha, \alpha^*) e^{\alpha^2}] |_{\alpha=\alpha^*=0}. \]

Here α and \( \alpha^* \) are formally treated as independent variables. Estimation of \( A_{m,n} \) from experimental data requires inversion of Eq. (1) when the Q-function is not known precisely. This can be a delicate procedure sensitive to statistical fluctuations of the data.

In Ref. [27], elements of quantum process matrix of a lossy channel were reconstructed from the experimental data with the help of regularized version of Glauber-Sudarshan P-functions [39] of operators |m⟩⟨n|. This approach approximates the calculation of derivatives in Eq. (2) by evaluation of a suitable linear combination of the experimental data. In Ref. [31], POVM elements of a single-photon detector were reconstructed from measurements on probe coherent states by solving a convex optimization problem that included an extra constraint.
which ensured a smooth structure of the reconstructed POVM elements. Later on, maximum-likelihood estimation was employed for reconstruction of quantum operations and detectors probed with coherent states \[39\] [40]. This latter approach avoids the complications with direct linear inversion \[2\], but it requires some truncation of the infinite-dimensional operator $\chi$.

In this paper, we investigate characterization of continuous variable quantum operations which is based on single-mode squeezed probe states and homodyne detection on output states. By using squeezed states instead of coherent states we avoid the problems with linear inversion of the data and we show that the matrix elements of quantum process $\chi$ in Fock basis can be determined by averaging suitable well behaved pattern functions \[37\] [39] over the homodyne data. Our procedure assumes that all probe states have the same variances of squeezed and anti-squeezed quadratures, and these variances need to be known and kept constant during the whole measurement. The probe states also need to be phase shifted and coherently displaced in a controlled way, which is feasible with current technology. Importantly, our procedure works for realistic mixed squeezed states and the only requirement is that the variance of the squeezed quadrature is below the coherent state level. Although we focus on linear reconstruction based on the formalism of pattern functions, the data could be processed by other means, such as the maximum likelihood estimation. Our work provides an important insight into the utility of squeezed states for tomography of quantum processes.

II. QUANTUM PROCESS TOMOGRAPHY

In what follows we shall consider characterization of a single-mode quantum operation $\mathcal{E}$. According to the Choi-Jamiolkowski isomorphism \[14\] [15], such operation can be represented by a positive semidefinite operator $\rho$ in Fock basis, $\chi = I \otimes \mathcal{E}(\Psi)$, \[3\] where $I$ stands for the identity channel and $\Psi = |\Psi\rangle\langle\Psi|$ denotes a density matrix of an infinitely squeezed EPR state,

$$|\Psi\rangle = \sum_{n=0}^{\infty} |nn\rangle. \tag{4}$$

The input-output transformation $\rho_{\text{out}} = \mathcal{E}(\rho_{\text{in}})$ can be expressed as

$$\rho_{\text{out}} = \text{Tr}_\text{in} \left[ \rho_{\text{in}}^T \otimes I \chi \right], \tag{5}$$

where $T$ denotes transposition in Fock basis, $I$ stands for the identity operator, and $\text{Tr}_\text{in}$ denotes partial trace over the input mode. In Fock basis, the formula \[5\] explicitly reads,

$$\rho_{\text{out},m,n} = \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \chi_{km,ln} \rho_{\text{in},k,l}. \tag{6}$$

Here $\rho_{m,n} = \langle m|\rho|n\rangle$ and $\chi_{km,ln} = \langle km|\chi|ln\rangle$. Identity channel $I$ is isomorphic to the EPR state \[4\], $\chi_I = \Psi$, and $\chi_{I,km,ln} = \delta_{km} \delta_{ln}$.

The input-output transformation \[5\] can be also formulated for phase-space representations. Let $W_{\text{in}}(x,p)$ and $W_{\text{out}}(x,p)$ denote the Wigner functions of input and output density operators $\rho_{\text{in}}$ and $\rho_{\text{out}}$, respectively, and let $W_{\chi}(x_{\text{in}},p_{\text{in}},x_{\text{out}},p_{\text{out}})$ denote the Wigner function of operator $\chi$. The partial trace \[5\] can be rewritten as an integral over the phase space of the input mode,

$$W_{\text{out}}(x_{\text{out}},p_{\text{out}}) = 2\pi \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} W_{\text{in}}(x_{\text{in}},-p_{\text{in}}) \times W_{\chi}(x_{\text{in}},p_{\text{in}},x_{\text{out}},p_{\text{out}}) dx_{\text{in}} dp_{\text{in}}.$$

where $W_{\text{in}}(x_{\text{in}},-p_{\text{in}})$ is a Wigner function of the transposed input state $\rho_{\text{in}}^T$.

Our goal is to establish a procedure for determination of the matrix elements $\chi_{km,ln}$ from experimental data. Formula \[5\] suggests that this could be achieved by probing the quantum operation $\mathcal{E}$ with one part of the EPR state $|\Psi\rangle$. To make this continuous-variable ancilla-assisted quantum process tomography \[3\] [10] experimentally feasible, the unphysical infinitely squeezed EPR state may be replaced with a two-mode squeezed vacuum with finite squeezing \[3\],

$$|\xi\rangle = \sqrt{1 - \lambda^2} \sum_{n=0}^{\infty} \lambda^n |nn\rangle, \tag{7}$$

where $\lambda = \tanh r$, and $r$ denotes the squeezing constant. After some algebra, we find that the elements of the quantum process matrix $\chi$ can be determined as properly rescaled elements of the output two-mode state.
\[ \sigma^{\lambda} = \mathcal{I} \otimes \mathcal{E}(\xi), \text{ where } \xi = |\xi\rangle \langle \xi|, \]
\[ \chi_{km,ln} = (1 - \lambda^2)^{-1} \lambda^{-(k+l)} \sigma_{km,ln}^{\lambda}. \]

If both modes of the output state \( \sigma^{\lambda} \) would be measured with homodyne detectors, see Fig. 1(a), then the matrix elements \( \sigma_{km,ln}^{\lambda} \) could be reconstructed by quantum homodyne tomography \[25, 26\]. Let \( \eta_A \) and \( \eta_B \) denote the overall detection efficiency of balanced homodyne detectors \( \text{HD}_A \) and \( \text{HD}_B \), respectively. A detector with efficiency \( \eta \) can be modeled as a lossy channel with transmittance \( \eta \) followed by an ideal detector with unit efficiency. The detectors measure rotated quadratures of the output modes on a particular measurement outcome. The detectors measure rotated quadratures of the output modes on a particular measurement outcome.

Here \( f_{m,n}(x, \eta) \) represent the loss-compensating single-mode pattern functions for density matrix elements in Fock basis. Explicit analytical expressions for \( f_{m,n}(x, \eta) \) are provided in Ref. \[39\]. Since these expressions are rather cumbersome, we do not reproduce them here. We only note that the pattern functions \( f_{m,n}(x, \eta) \) are well defined for \( \eta > \frac{1}{2} \) and they diverge when \( \eta \to \frac{1}{2} \).

### III. SINGLE-MODE PROBE STATES

In this section, we will propose a procedure for quantum process tomography with single-mode squeezed probe states. In particular, we will exploit the fact that the ancilla assisted process tomography with a two-mode squeezed vacuum state \( |\xi\rangle \) and individual single-mode homodyne measurements on the output modes is equivalent to preparation of a specific ensemble of displaced and rotated single-mode squeezed states of mode B, followed by probing the quantum operation \( \mathcal{E} \) with these states \[23\]. To see this equivalence, we rewrite the joint quadrature distribution as

\[ P(x_A^\theta, x_B^\phi; \theta, \eta_A, \phi, \eta_B) = P(x_A^\theta; \theta, \eta_A) \times P(x_B^\phi; \phi, \eta_B|x_A^\theta; \theta, \eta_A), \]

where \( P(x_A^\theta; \theta, \eta_A) \) is the probability density of measurement outcomes \( x_A^\theta \) on mode A, and \( P(x_B^\phi; \phi, \eta_B|x_A^\theta; \theta, \eta_A) \) is the conditional probability density of measurement outcomes of quadrature \( x_B^\phi \) on mode B provided that a particular measurement outcome \( x_A^\theta \) was obtained on mode A.

Here \( x_J \) and \( p_J \) denote the amplitude and phase quadratures of mode \( J \), \( [x_J, p_K] = i \delta_{JK} \), and \( x_A^{\theta, \text{vac}} \) and \( x_B^{\phi, \text{vac}} \) represent quadratures of auxiliary vacuum modes. This measurement samples the joint quadrature distribution \( P(x_A^\theta, x_B^\phi; \theta, \eta_A, \phi, \eta_B) \) and the matrix elements \( \chi_{km,ln} \) can be determined by averaging the so-called pattern functions over the quadrature statistics \[37–39\].

Since mode A is in a thermal state, the probability \( P(x_A^\theta; \theta, \eta_A) \) does not depend on \( \theta \), and all quadratures \( x_A^\theta \) exhibit Gaussian distribution with zero mean and variance

\[ V_A = \frac{1}{2} [\eta_A \cosh(2r) + 1 - \eta_A]. \]

This formula accounts for imperfect detection with efficiency \( \eta_A \), and \( \frac{1}{2} \cosh(2r) \) is the variance of quadratures of mode A of the pure two-mode squeezed vacuum state \[7\].Explicitly, the probability density reads

\[ P(x_A^\theta; \theta, \eta_A) = \frac{1}{\sqrt{2\pi V_A}} \exp \left[ -\frac{(x_A^\theta)^2}{2V_A} \right]. \]

Homodyne detection of quadrature \( x_A^\theta \) on mode A of the two-mode squeezed vacuum state \[7\] prepares the other mode B in a coherently displaced squeezed state with squeezing ellipse rotated by angle \( -\theta \), see Fig. 1(b). This rotation follows from the identity

\[ U_A(\theta) U_B(-\theta)|\xi\rangle = |\xi\rangle, \]

where \( U(\theta) = e^{-i\theta} \) is a unitary phase shift operator. Measurement of a rotated quadrature \( x_A^\theta \) on mode A is thus fully equivalent to measurement of quadrature \( x_A^\theta \), followed by rotation of mode B by \( -\theta \). The covariance matrix of the conditionally prepared state does not depend on the measurement outcome \( x_A^\theta \), and the coherent displacement \( d \) is linearly proportional to the measurement outcome.

Let \( V_- \) and \( V_+ \) denote the variances of squeezed and anti-squeezed quadratures of the conditionally prepared state, and let \( d \) denote the coherent displacement of the
squeezed quadrature of this state. It follows from the above discussion that, without loss of generality, we can assume \( \theta = 0 \) in our derivation of \( V_x \), \( V_+ \), and \( d \). It is convenient to collect the quadrature operators of modes A and B into a vector \( z = (x_A, p_A, x_B, p_B) \) and define a two-mode covariance matrix \( \gamma_{jk} = \langle \Delta z_j \Delta z_k + \Delta z_k \Delta z_j \rangle \), where \( \Delta z_j = z_j - \langle z_j \rangle \). Covariance matrix of a two-mode squeezed vacuum state [7] whose mode A was transmitted through a lossy channel with transmittance \( \eta_A \) reads,

\[
\gamma_{AB} = \begin{pmatrix}
2V_A & 0 & K & 0 \\
0 & 2V_A & 0 & -K \\
K & 0 & 2V_B & 0 \\
0 & -K & 0 & 2V_B \\
\end{pmatrix},
\]

where \( V_B = \frac{1}{2} \cosh(2r) \) and \( K = \sqrt{\eta_A} \sinh(2r) \).

Since there are no correlations between the \( x_A \) and \( p_B \) quadratures, measurement of \( x_A \) does not influence \( p_B \), whose variance remains equal to \( V_B \) and \( \langle p_B \rangle = 0 \),

\[
V_+ = \frac{1}{2} \cosh(2r).
\]

In contrast, the measurement of \( x_A \) will reduce fluctuations of \( x_B \) due to the correlations between \( x_A \) and \( x_B \). The resulting (conditional) variance \( V_- \) of \( x_B \) can be calculated by minimizing the variance of \( x_B - gx_A \) over a tunable gain \( g \). The optimal gain reads \( g_{\text{opt}} = K/(2V_A) \), which yields

\[
V_- = \frac{1}{2} \eta_A + \left( 1 - \eta_A \right) \cosh(2r).
\]

Moreover, the coherent displacement \( d \) of the conditionally prepared state of mode B is given by \( \langle x_B \rangle = g_{\text{opt}} x_A \), which explicitly reads

\[
d = \frac{\sqrt{\eta_A} \sinh(2r)}{\eta_A \cosh(2r) + 1 - \eta_A} x_A.
\]

The variances \( V_- \) and \( V_+ \) of squeezed and anti-squeezed quadratures of the probe single-mode state determine the effective detection efficiency \( \eta_A \) of HD_A and the parameter \( \lambda \) of the (virtual) two-mode squeezed vacuum state [7]. By inverting formulas (16) and (17), we get

\[
\eta_A = \frac{2(V_+ - V_-)}{(2V_+ - 1)(2V_- + 1)},
\]

and

\[
\lambda = \sqrt{\frac{2V_- - 1}{2V_+ + 1}}.
\]

The effective detection efficiency \( \eta_A > \frac{1}{2} \) if and only if the probe state is squeezed and \( V_- < \frac{1}{2} \). This establishes single-mode squeezing as a valuable resource for continuous variable quantum process tomography. If the probe state is pure, \( V_+ = 1/(4V_-) \), then \( \eta_A = 1 \). If \( V_- < \frac{1}{2} \), then the efficiency is a decreasing function of \( V_- \) and in the limit \( V_+ \to \infty \) we get \( \eta_A = 1/(1 + 2V_-) \). The coherent displacement [18] of mode B can be expressed in terms of the quadrature variances as follows,

\[
d = \sqrt{2(1 - V_-)} \sqrt{\frac{2V_- + 1}{2V_+ + 1}} x_A.
\]

Formula (11) together with the above results suggests that the joint quadrature distribution \( P(x_A^\theta, x_B^\phi, \theta, \eta, \phi) \) can be sampled as follows. Generate random \( x_A^\theta \) drawn from the Gaussian distribution (13) and a random \( \theta \) and \( \phi \) drawn from a uniform distribution in the \([0, 2\pi]\) interval. Prepare a single-mode squeezed Gaussian state with variances \( V_- \) and \( V_+ \) and displacement \( d \), rotated in phase space by \( -\theta \), as illustrated in Fig. 1(b). Send this probe state through the quantum channel \( \mathcal{E} \) and measure a rotated quadrature \( x_B^\phi \) of the output state with a homodyne detector. Note that the squeezing properties of the input probe states do not depend on \( x_A^\theta \) and \( \theta \), hence a source producing squeezed states with a fixed amount of squeezing and anti-squeezing is sufficient.

The improvement achieved by squeezed probe states in comparison to coherent probe states comes at a cost of somewhat increased experimental difficulty. In particular, the variances \( V_+ \) and \( V_- \) of the probe squeezed states need to be precisely characterized, which can be achieved by routine homodyne detection, and these parameters have to be kept constant during the whole tomographic measurement. Moreover, the orientation of the squeezing ellipse should be fully under control and tunable to any required angle \( \theta \). Finally, the ability to coherently displace the squeezed state is also required, which can be achieved e.g. by mixing it with an auxiliary coherent beam on a highly unbalanced beam splitter [40].

IV. TOMOGRAPHY OF QUANTUM MEASUREMENTS

The proposed method can be also adapted to tomographic characterization of quantum measurements [31-33, 41-44]. Consider a detector D which can respond with \( K \) different outcomes. Each outcome is associated with a POVM element \( \Pi_k \) and the probability to observe an output \( k \) for input state \( \rho \) reads \( p(k) = \text{Tr}[\Pi_k \rho] \). Consider now an ancilla-assisted quantum detector tomography [43, 44], where the detector is probed with one part of a two-mode squeezed vacuum state, see Fig. 2(a). The conditionally prepared state of mode A corresponding to measurement outcome \( k \) on mode B can be expressed as

\[
\rho^k = (1 - \lambda^2) \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \lambda^{m+n} \Pi_{m,n}^k |n\rangle \langle m|.
\]

The state is not normalized and its trace is equal to probability of observing the outcome \( k \),

\[
\text{Tr}(\rho^k) = \langle \xi | I_A \otimes \Pi_B^k | \xi \rangle.
\]
The matrix elements of $\Pi^k$ can then be immediately obtained from Eq. (24), where the parameter $\lambda = \tanh r$ is determined by the variance of anti-squeezed quadrature $V_-$ of the probe state, see Eq. (16).

V. CONCLUSIONS

In summary, we have proposed a procedure for tomographic characterization of continuous variable quantum operations which employs homodyne detection and single-mode squeezed probe states with a fixed degree of squeezing and anti-squeezing and a variable displacement and orientation of squeezing ellipse. We have shown that the elements of quantum process matrix $\chi$ in Fock basis can be estimated by averaging suitable pattern functions over the homodyne data. The pattern functions are well behaved provided that the probe state is squeezed and $V_- < \frac{1}{2}$. For the sake of simplicity, we have considered tomography of a single-mode operation $E$. However, the method can be straightforwardly extended to multimode operations. For tomography of $N$-mode operation, one would have to use $N$ independent single-mode squeezed states and measure each output mode with an independent homodyne detector. While we have focused on linear reconstruction procedure based on pattern function formalism, other methods of data processing would be also possible. For instance, one may utilize the widely employed maximum-likelihood estimation, or other approaches. Given its relative simplicity and practical feasibility, the present procedure is likely to find applications in the characterization of continuous variable quantum operations and measurements.

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