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Estimating the dynamical error map of single-qubit gates under non-Markovian phase noise

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Quantum computers are inherently susceptible to the impact of noise. Precise characterization and effective noise mitigation techniques are imperative to progressively overcome the limitations posed by a noisy system such as enabling large-scale quantum computing. Motivated by this necessity, we introduce a newly developed microscopic model designed to provide a more compact parametrization of noisy single-qubit gates. Our analytic model is the first to go beyond the conventional practice of modelling depolarizing errors as the exclusive noise source, allowing us to predict the quantum processor's performance even in regimes where the dynamics can be proven to be non-Markovian. This leads to an enhancement in describing the average channel infidelity with numerically exact evolution of noisy single-qubit gates by at least one order of magnitude, while the model's calculation requires solely the noise power spectral density as input.
To validate and compare the analytical model against experimental results, we apply quantum process tomography and randomized benchmarking techniques to a trapped-ion quantum information processor based on singly ionized Calcium-40. As expected, we find, that our model treating phase noise as the sole error source provides a close lower bound on the average gate infidelity obtained through randomized benchmark and quantum process tomography. Moreover, our model outperforms previous gate infidelity metrics based on filtered power spectral densities and serves as a promising extension to established quantum characterization, verification, and validation protocols. For example, it introduces a more efficient parametrization of gate sets characterized in gate set tomography, thereby significantly reducing the resource requirements associated with this demanding procedure.

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