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Towards High-Fidelity Gates for the Nitrogen-Vacancy Center in Diamond

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Abstract: We realize high-fidelity gates for the two-qubit system formed by NV center. Using gate set tomography, we report gate fidelities exceeding 99%, and analyze the origin of the errors.

1. Introduction

Spin defects in solid-state materials are promising candidates for exploring quantum information applications due to their long coherence time and optical interfaces. A potential application is the realization of quantum networks for quantum communication and distributed quantum computing [2]. Recently, early demonstrations such as a multi-node networks [6, 8] and quantum error correction [1, 5] were realized using the nitrogen-vacancy(NV) center in diamond. A key challenge towards expanding the number of qubits and the complexity of algorithms, is to further improve the gate fidelities and reduce crosstalk between qubits.

In this work, we use gate set tomography(GST) [3, 7] to optimize and characterise a complete set of single- and two-qubit gates for the NV center spin system. Using the information that the obtained process matrixes provide, we discuss the limitation of the gates. We apply this method to both an electron-nitrogen nuclear spin two-qubit system and an electron-carbon nuclear spin two-qubit system.

2. Gate set tomography on electron-nitrogen two-qubit system

When preparing qubit gates, the competition between the gate speed and the decoherence time scale of the qubits is the main factor to prepare a good gate. In this context, we first design, optimize and characterize gates for the electron-nitrogen two-qubit system within a single NV center in an isotopically purified diamond (target ^{13}C concentration of $\sim 0.01\%$). This (mostly) removes the ^{13}C spin bath as a noise source.

We design a universal set of gates based on dynamical decoupling radio frequency(DDRF) gates between the electron spin and nitrogen nuclear spin [4]. Using GST, we characterize the process matrix of a universal gate set for the two spin-qubits (See Fig. 1) and obtain gate fidelities exceeding 99% for all gates. Furthermore, we confirm the validity of the process matrices reported from the GST reports by preparing test quantum circuits that repeatedly swap a quantum state between the two spins (Fig. 1b). The evolution of the electron spin during the circuit is tracked and measured by preparing the electron in the six cardinal states on the Bloch sphere. The measurement result is accurately predicted using the process matrices of the gates reported by GST even for a circuit with more than 800 gates.

3. Gate set tomography on electron-carbon two-qubit system

To expand the number of qubits in a single NV system, we additionally investigate gates between the NV electron spin and carbon nuclear spins [4]. For this, we use a natural abundance diamond with a 1.1% concentration of ^{13}C. We use GST to characterize a complete set of gates on an electron-carbon nuclear spin two-qubit system, and obtain two-qubit gate fidelities exceeding 99% from the resulting process matrices. These results make it possible to analyze the error generators of the gate processes and thus provide a path towards further improving the gate fidelities and studying cross talk in multi-qubit systems.

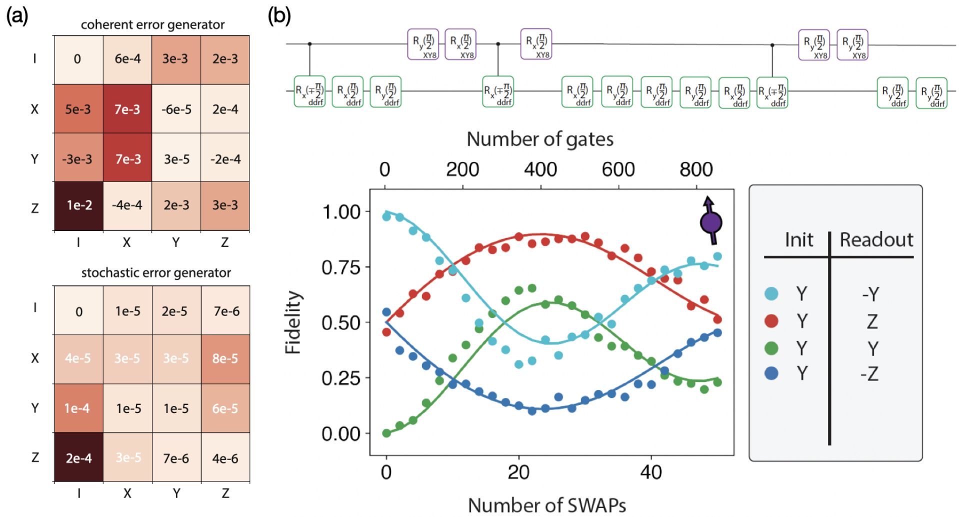

Fig. 1. **GST process matrix overview. a.** Example error generator of a two-qubit gate for the electron-nitrogen two-qubit extracted from the reported process matrix. The top matrix shows the coherent error within the gate and the bottom matrix shows the stochastic error within the gate. **b.** Example quantum circuit for a SWAP gate compiled from the characterized gates (top) and the measurement of the evolution of the electron spin while running the circuit (bottom). The circle markers show the measurement result and the solid lines shows the prediction using the measured process matrices.

4. Conclusion

We characterised process matrices and fidelities of the single- and two-qubit gates for NV centers using GST. From the process matrices, we obtain two-qubit gate fidelities exceeding 99%. Furthermore, we retrieve the limitations of the gates using the information in the reported process matrix and the error generators. The full characterisation of a set of universal gates and the high gate fidelities obtained are key steps towards distributed quantum computation and quantum networks using spin qubits in solid state materials.

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