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Bayesian quantum phase estimation on an integrated Silicon photonic device

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Abstract: We demonstrate a Bayesian approach for practical and robust implementation of the quantum phase estimation algorithm. We implement it on a reconfigurable Silicon quantum photonic device, demonstrating its importance for future quantum applications.

1. Introduction

Quantum computers promise to revolutionize scientific computing by providing exponential speedups over their classical counterparts. This prospect stimulated a lot of interest in the scientific community and great efforts are being made towards the realization of quantum machines able to outperform classical ones. A fundamental component of many quantum algorithms is the Quantum Phase Estimation (PE), being used e.g. for large number factorization [1] and quantum simulation of physical systems [2]. PE is an indispensable subroutine for these applications as it exponentially reduces the number of experiments needed to solve such problems. The first proof-of-principle demonstrations of PE have relied on Kitaev's algorithm and its adaptive version [3], called Iterative Phase Estimation Algorithm (IPEA), that requires a small number of qubits and logic gates and is thus appealing for small scale implementations. These algorithms use the circuit in Fig. 1b to iteratively estimate the bits of the eigenphase ϕ . However, a common criticism to these is that the success probability of the algorithm decreases exponentially with experimental noises, e.g. imperfect operations and decoherence of the system, and can thus be impractical to perform on non-error-corrected devices [4]. New and more robust approaches to PE are thus required for near future experimental implementations.

Here we report the first experimental realization of a new Bayesian approach to PE [5], called Rejection Filtering Phase Estimation (RFPE), which promises to overcome these issues and also allows to estimate its own error. We show the performance of RFPE on a state-of-the-art reconfigurable quantum photonic chip, shown in Fig. 1a, which is able to execute a non-compiled logic circuit as in Fig. 1b, achieving with high probability chemical accuracy after only 50 measurements. This device allows us to study RFPE under various types of realistic noises, providing experimental evidence of its practicability and robustness for future applications.

2. Results

The device schematics used to implement the arbitrary controlled-unitary (CU) is shown in Fig. 1a. It employs two integrated SFWM photon pair sources to generate an entangled path-encoded state of two qubits. The two different path-encoded components of the target qubit go through different unitaries, i.e. $\hat{1}$ (top) and \hat{U}^M (bottom), yielding a superposition of circuits that returns the state $(|0\rangle|\phi\rangle + |1\rangle U^M|\phi\rangle)/\sqrt{2}$ after the two spatial modes are mixed. This accomplishes the arbitrary non-compiled CU operation required to execute the logic circuit in Fig. 1b. Single qubit operations on the control qubit can be performed by a Mach-Zehnder interferometer and phase shifters.

In RFPE each time a measurement is obtained from an experiment a Bayesian update is used to obtain a posterior probability distribution of the phase. RFPE then adaptively proposes a new experiment that maximizes information gain based on the updated distribution. Fast and precise reconfiguration of the heaters in our chip allows to reconfigure

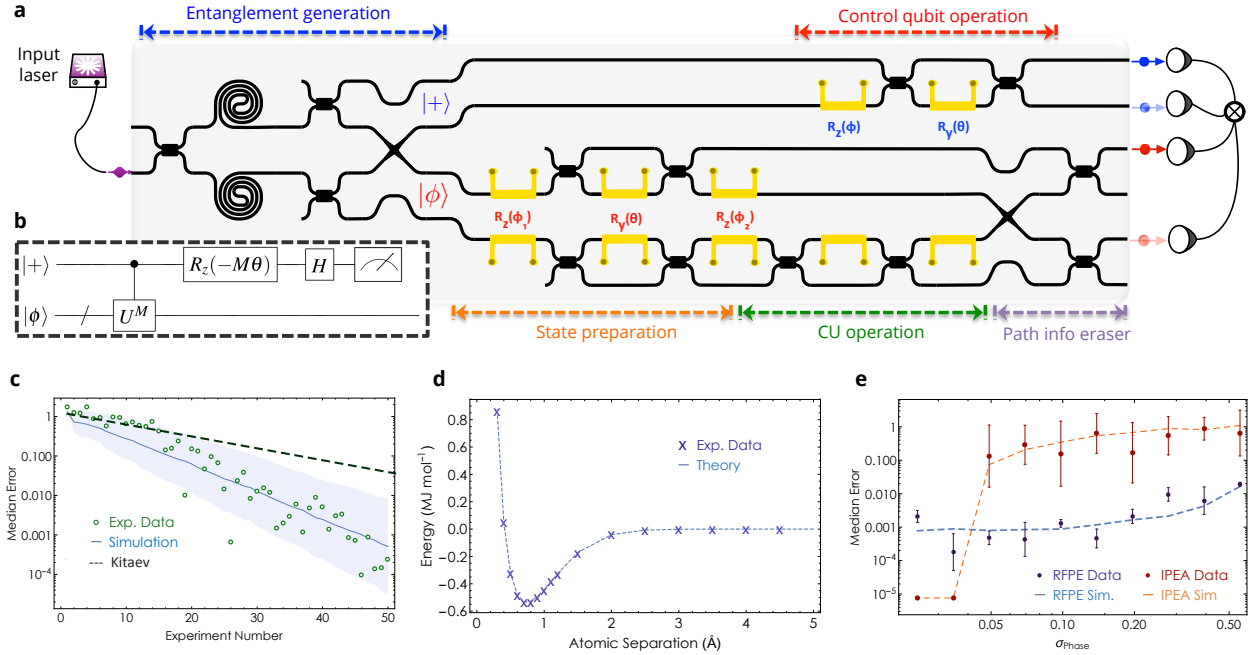


Fig. 1. **a)** Schematic of the integrated device used for the implementation of the arbitrary CU. **b)** Logic quantum circuit for phase estimation. **c)** Exponentially fast convergence of the experimental RFPE (shaded area: one standard deviation). **d)** Experimental values of bond energies of the H_2 molecule obtained by RFPE with 50 iterations. **e)** Experimental study of median errors in RFPE and IPEA as a function of the phase noise happened in both state preparation and gate operations.

experiments in the hundreds of kHz rate, that makes adaptive protocols like RFPE practical on our device. Fig. 1c shows that errors decrease exponentially with number of experiments. We run RFPE with 50 iterations to scan the bonding energy of molecular hydrogen (H_2) for different atomic distances, as reported in Fig. 1d. The precision of these estimated energies is 3 kJ/mol , higher than the chemical accuracy, showing the reliability of the algorithm for quantum simulation tasks. We then introduce controllable noises in our experiment in order to study the behavior of both RFPE and IPEA on non-fault-tolerant devices. In Fig. 1e we report the results for errors arising from noisy implementations of both state preparation and CU. To experimentally simulate this kind of noise, for each heater manipulating the target qubit/gate we replace the correct phase $\bar{\varphi}$ required to implement the transformation with a synthetic value φ sampled from a gaussian distribution $\varphi \sim \mathcal{N}(\bar{\varphi}, \sigma_{\text{phase}})$. Fig. 1e shows that while IPEA becomes unreliable even for very small noise, RFPE maintains a precision of $\approx 10^{-2}$ in the phase estimation even when $\sigma_{\text{phase}} \geq 0.5 \text{ rad}$, corresponding to average fidelity ≤ 0.94 for the state and ≤ 0.92 for the unitary. We observed qualitatively similar results also for errors arising from decoherence and coupling losses, proving the robustness claimed in [5].

3. Conclusions

We exploited the high-precision controllability and stability of state-of-the-art quantum photonic technology to achieve the first experimental demonstration of the RFPE, a novel Bayesian quantum phase estimation. The experimental results show a strong enhancement in the robustness to noise and decoherence, verifying the claims made in [5], and make RFPE appealing for near-future applications in quantum simulation and computation on non-fault-tolerant devices.

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