A Programmable Qudit-based Quantum Processor

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Abstract: We designed, fabricated, and characterized a programmable qudit-based quantum processor on silicon and several quantum algorithms were implemented using qudits which shows the logarithmic speed-up, counting rate acceleration and accuracy improvement of the qudit processor.

1. Introduction

Qudit-based quantum technology has the advantages of larger Hilbert space, stronger bell nonlocality, better error-tolerance and natural implementation in optical systems [1]. Recent years, significant progress has been made in the generation and measurement of high-dimensional quantum states [2], the improvement of quantum communication capacity, strengthen in Bell’s non-local properties and reduce in measurement loophole. Meanwhile, universal quantum computation can also be realized using qudit and requires fewer resources for quantum error correction, improving the performance of quantum algorithms.

Our work shows the enhanced capacity, accuracy, and efficiency of qudit-based quantum computing technology and we also demonstrated the great importance of programmable quantum processor with qudits which supplies more than one million high-fidelity quantum state generations, operations and projections.

2. Results

We designed the integrated quantum photonic circuit and use 248nm deep ultraviolet lithography to fabricate the silicon-based quantum photonic chip shown in Fig 1A on 220nm silicon-on-insulator (SOI) [3]. We pump the four light sources simultaneously at 1550nm and the integrated asymmetric Mach-Zehnder interferometer (AMZI) after each light source are used to separate the signal and idler photons, which generated the 4-dimensional Bell state. Together with the combination of on-chip integrated Mach-Zehnder interferometers (MZI) [4], we achieved high-dimensional quantum state generations, unitary operations, coherent state compression, and projection measurements. All of these configurations can be programmed for arbitrary choices.

A complete set of 16 4-dimensional bell states were generated and the quantum state tomography(QST) were used to reconstruct the density matrix of them [5]. We get an average fidelity of 95.4%. One of the density matrix
was shown at Fig 1B. We also implement the quantum process tomography (QPT) of the generalized CNOT gate called MVCX with process fidelity 95.2% [6].

Experimentally, 2-photon 4-dimension state has the coincidence counting rate $\sim$kHz. For comparison, rates of qubits with the same capacity features $\sim$mHz [7], an advantage of qudit regarding faster speed of computation.

The advantage of high-dimensional quantum computing can also be shown from algorithms. We designed and programmed the 4-dimensional iterative quantum phase estimation algorithm (IPEA) with the quantum circuit in Fig 1E on chip [8]. Bottom shows the calculation result of eigenvalue $e^{0.0301101322(2\pi)}$ of $F^{0.77}$, where $F$ is the 4-dimension quantum Fourier transform.

Using qudit to drive the quantum algorithm, we get the measurement result quaternary each time which improves the accuracy and speed of the calculation. We also plot the variation of calculation accuracy in different dimensions with the numbers of iterations in Fig 1F. Such improvement implies the enhanced accuracy and efficiency of the qudit quantum algorithm and quantum computers in the future.

In summary, we have demonstrated the first high-fidelity programmable qudit quantum processor on silicon with more than 1 million configurations, and enabling qudit quantum computation with the capacity, accuracy and efficiency improvement.

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