Quantum computation via multilevel superconducting circuit

Evgeny O. Kiktenko,[1,2,*] Aleksey K. Fedorov,[1,3] Alexey A. Strakhov,[4] and Vladimir I. Man'ko[4,5]

[1]*Bauman Moscow State Technical University, 2nd Baumanskaya St., 5, Moscow 105005, Russia*
[2]*Geoelectromagnetic Research Center of Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, PO Box 30, Troitsk, Moscow Region 142190, Russia*
[3]*Russian Quantum Center, 100 Novaya Street, Skolkovo, Moscow 143025, Russia*
[4]*Moscow Institute of Physics and Technology (State University), Moscow Region 141700, Russia*
[5]*P. N. Lebedev Physical Institute, Russian Academy of Sciences, Leninskii Prospect 53, Moscow 119991, Russia*

Qubit systems are of paramount importance in quantum information theory. Realizations of qubit are usually considered by application of distinct physical objects with two degrees of freedom such as two-level atoms, polarization of photons, 1/2-spin systems, and many others.

In the present work, we report about exploring of possibilities to design many-qubit system using a single anharmonic quantum oscillator. Our investigation is motivated by recent significant experimental progress in manufacturing and manipulation with multilevel artificial atoms realized via superconducting quantum circuits [1].

In our study, we consider a two-qubit system realized by five-level superconducting quantum circuit. The first four stationary energy states are used for encoding vectors of two-qubit computational basis and the fifth ancillary level is used for implementation of quantum logic gates for information processing (see Fig. 1). The fifth ancillary level is assumed to be unoccupied.

The operation with the system could be realized by applying θ-pulses of rotation around x-axis of Bloch sphere related to particular pair of energy levels, that is possible due to anharmonicity of the potential.

First of all, the appropriate sequences of such pulses allow to prepare two-qubit entangled states with equal level of purity as well as states with identical reduced density matrices. This scheme can be used for experimental verification of entropic inequalities, related with the quantity $\log N$ with N being the dimensionality of the Hilbert space [2], in noncomposite quantum systems.

Furthermore, the sequence of θ-pulses applied only to the first four levels of the circuit allow to implement only operators belonging to the SU(4) group, *e.g.*, Hadamard and NOT gates, acting on particular qubits of two-qubit system. This is a crucial reason for employing the fifth level, which allows to apply operators from SU(5) group, effectively realizing two-qubit gates with matrix beyond SU(4) group.

That trick opens a way to constructing the universal set of two-qubit gates consisting of Hadamard, $\pi/8$ and CNOT gates. Thus, by using this universal set of gates we propose a scheme for realization of the seminal two-qubit algorithm — the Deutsch–Jozsa algorithm [3] — in a multilevel superconducting circuit. This setup is highly promising for study of computational speed-up in single qudit realizations of oracle-based algorithms [4].

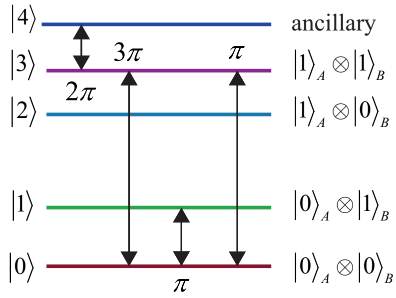

FIG. 1. Implementation of Controlled-NOT gate in a single five-level superconducting circuit. The first four levels are used for the state storage and the fifth level is employed for realization of gates with matrices beyond the SU(4) group. The operation with the system is realized by applying θ-pulses of rotation around x-axis of Bloch sphere related to particular pair of energy levels.

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* evgeniy.kiktenko@gmail.com

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