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Tunable qubit-cavity gates for digital quantum simulations in circuit QED

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Digital quantum simulation (DQS) is a promising application of quantum computers. Typically, short Trotter step sizes are required to realise accurate DQS. In the context of Trotterised DQS, it is also useful to be able to tune interaction times and even implement “negative-time” gates, when implementing higher-order digitisation algorithms and to control the amount of digitisation error, especially to stay below Trotterisation thresholds [1]. In superconducting qubit systems, one of the most widespread methods for implementing qubit-qubit and qubit-cavity gates is through fast frequency tuning of qubits via magnetic flux, particularly for planar chip architectures. It is also useful to be able to implement fast-flux-tuned qubit-cavity gates, either for additional control gates for 3D-qubit or higher-dimensional oscillator qubit toolboxes, or for simulations involving directly-encoded oscillator modes, such as the quantum Rabi model [2]. Yet implementing gates for short interaction times using square pulses can be extremely challenging due to finite system bandwidths arising from electronics or flux control, and the precision of gate tunability is limited by the sampling rates of the arbitrary waveform generators.

In this work, we show that novel smooth-shaped qubit-cavity flux tuning can be used to realise low-bandwidth pulses that do not require flux pulse predistortion, highly tunable gate parameters, ultrashort effective pulse lengths, and negative-time evolution. We design different techniques for achieving high-fidelity gates. Using relevant experimental system parameters [2], we show that smooth pulses applied to a transmon can simulate high-fidelity qubit-cavity interactions with short effective interaction times. These pulses extend the available quantum computing gate set with useful potential applications for quantum simulations, including for studying advanced Trotterisation techniques and novel phenomena such as the Rabi quantum phase transition, where extreme coupling regimes are required.

[1] C. Kargi et al., arXiv:2110.11113 (2021).

[2] N. K. Langford et al., Nature Communications 8, 1715 (2017).

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