Tunable "adiabatic" 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 and avoid digital aliasing effects. In the context of Trotterised DQS, it is also useful to be able to tune the step size when implementing higher-order digitization algorithms and to control the amount of digitization error, especially to stay below recently studied 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. Yet implementing gates for short interaction times can be extremely challenging due to finite system bandwidths arising from electronics or flux control, and introducing smooth-shaped "adiabatic" flux pulses for qubit-qubit gates was a key step towards overcoming these electronics-related limitations to help circuit QED systems reach critical two-qubit error thresholds. In recent years, it has come to be recognized that fast-flux-tuned qubit-cavity (Jaynes-Cummings) gates can also be valuable tools for digital quantum simulations involving oscillator modes such as the quantum Rabi model [2].

In this work, we show that novel smooth-shaped qubit-qubit and qubit-cavity flux tuning can be used to realise low-bandwidth pulses, highly tunable gate parameters, ultrashort effective pulse lengths, and even negative-time evolution. We introduce a new analytical method for studying these pulses and design different techniques for achieving high-fidelity gates. Using relevant experimental system parameters [2], we show that smooth pulses applied to ideal tunable qubit can simulate effective short qubit-cavity interactions with >99% fidelity [Fig. 1]. These pulses extend the available quantum computing gate set and have important applications for quantum simulations [3], including for studying novel phenomena such as the Rabi quantum phase transition, where extreme coupling regimes are required, and advanced Trotterisation techniques.

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

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

[3] L. Lamata et al., Advances in Physics: X 3 (1), 1457981 (2018).

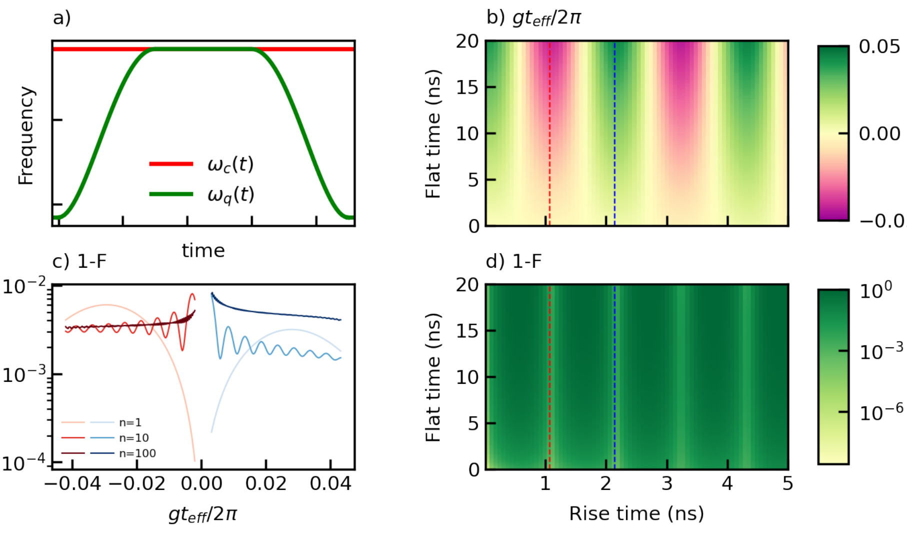

Fig. 1 By varying rise time and flattop of a) smooth trapezoidal pulse it is possible to simulate b) continuous range of values of effective square pulse duration gt_{eff}. The red and blue cuts show parameters where gt_{eff} can be simulated with high fidelity. c) Comparison of the simulation infidelity of these cuts for different number of gates n, where infidelity is calculated between U^n_{smooth} and $U^n_{ideal}(gt_{eff})$ the unitaries of smooth trapezoidal and ideal square pulse with effective phase gt_{eff} respectively. d) Infidelity landscape between U_{smooth} and $U_{ideal}(gt_{eff})$.