UNIVERSAL GATE SET FOR CONTINUOUS-VARIABLE QUANTUM COMPUTATION WITH MICROWAVE CIRCUITS

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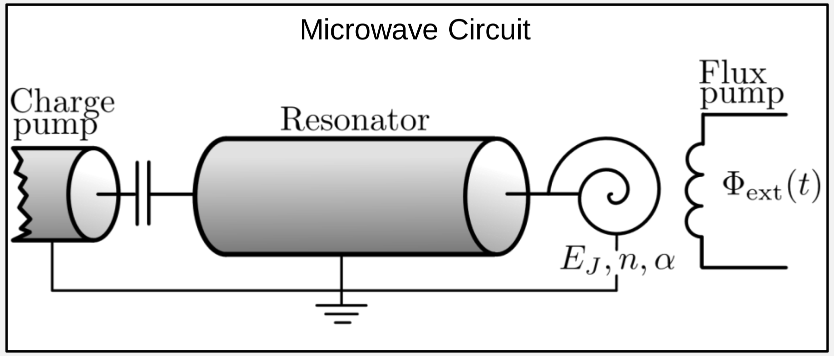
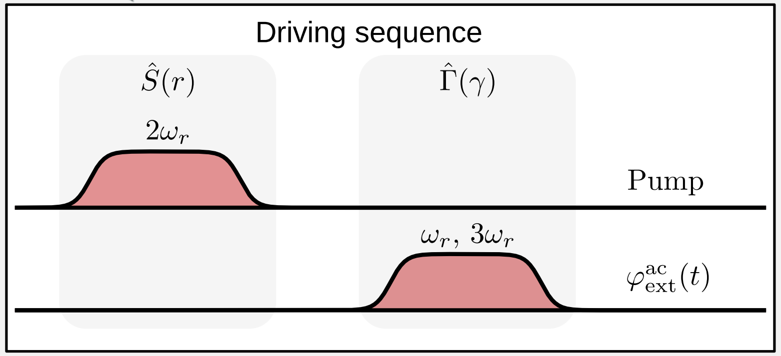
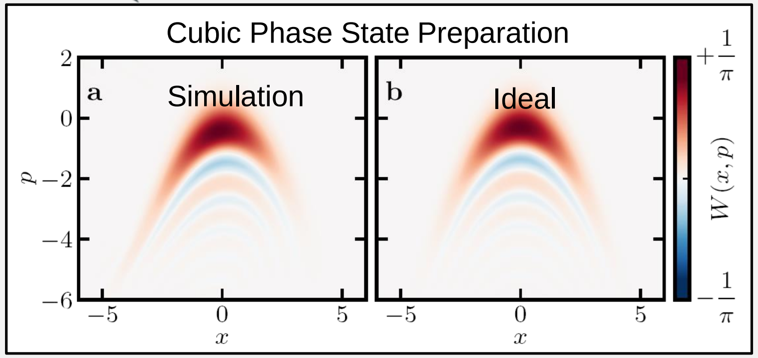






CONTINUOUS-VARIABLE UNIVERSAL GATE SET[1]

Definition

Definition (CV Universality).
A set of continuous quantum operations will be termed universal for a class of transformations if one can, by a finite number of applications of these operations, approach arbitrarily closely to any transformation of this class.

$$\left\{ \mathrm{e}^{i s_x \hat{x}}, \mathrm{e}^{i\eta\hat{x}^2}, \mathrm{e}^{i\frac{\pi}{4}\left(\hat{x}^2+\hat{p}^2\right)}, \mathrm{e}^{i\hat{x}_m \otimes \hat{p}_n}, \mathrm{e}^{i\gamma\hat{x}^3} \right\}$$

$$\mathrm{e}^{-i\hat{A}\delta t}\mathrm{e}^{-i\hat{B}\delta t}\mathrm{e}^{i\hat{A}\delta t}\mathrm{e}^{i\hat{B}\delta t} = \mathrm{e}^{[\hat{A},\hat{B}]\delta t} + \mathcal{O}\left(\delta t^3\right)$$

Applications

Simulate arbitrary polynomial $\hat{H}(\hat{x},\hat{p})$
Marshall *et al.*, PRA **92**, 063825 (2015)
Deng *et al.*, Sci. Rep. **6**, 22914 (2016)

Quantum Monte Carlo integration
Rebentrost *et al.*, arXiv:1809.02579

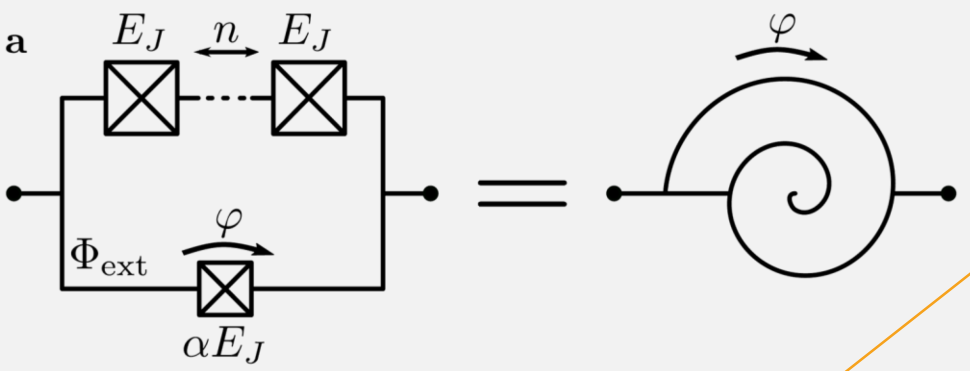
Optimization of continuous functions
Verdon *et al.*, arXiv:1902.00409

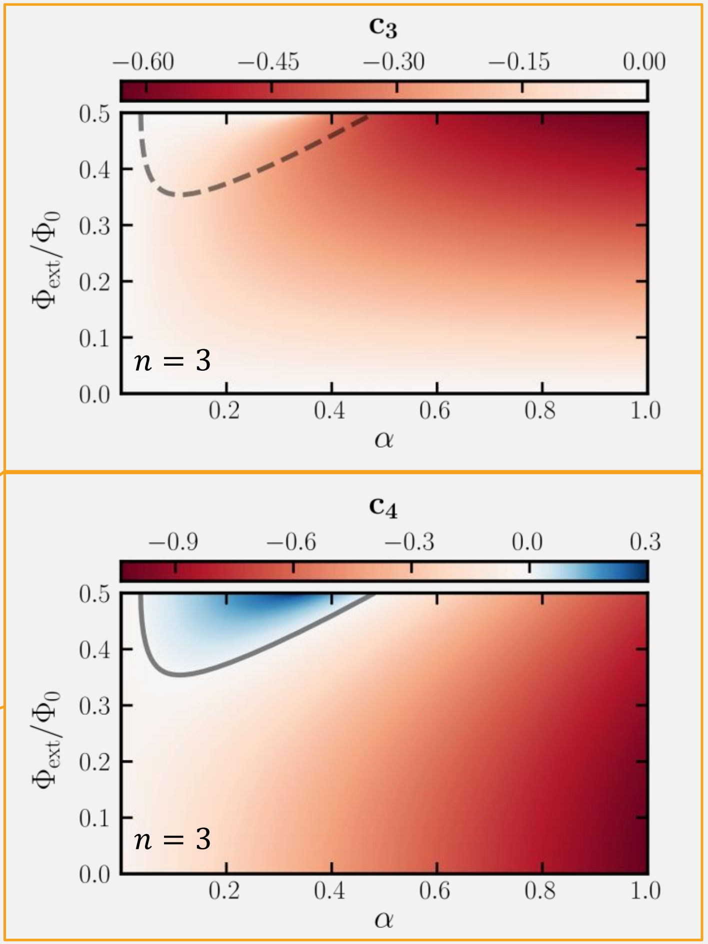
Review
Weedbrook *et al.*, RMP **84**, 621 (2012)

1: Lloyd & Braunstein, PRL **82**, 1784 (1999)

THE SUPERCONDUCTING NONLINEAR ASYMMETRIC INDUCTIVE ELEMENT[1]

$$U_{\mathrm{SNAIL}}(\varphi) = -\alpha E_J \cos\varphi - n E_J \cos\frac{\varphi_{\mathrm{ext}} - \varphi}{n}$$





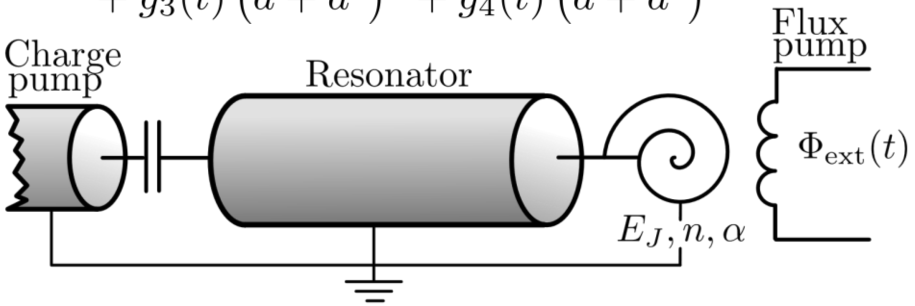
$$\frac{1}{E_J} U_{\mathrm{SNAIL}}(\varphi) = \sum_{m=2}^{\infty} \frac{c_m}{m!}\varphi^m = \frac{c_2}{2!}\varphi^2 + \frac{c_3}{3!}\varphi^3 + \frac{c_4}{4!}\varphi^4 + \mathcal{O}(\varphi^5)$$

1: Frattini *et al.*, APL **110**, 222603 (2017)

MICROWAVE ARCHITECTURE

Design

$$\hat{H} \approx \omega_r \hat{a}^\dagger \hat{a} + g_1(t)\left(\hat{a} + \hat{a}^\dagger\right) + g_2(t)\left(\hat{a} + \hat{a}^\dagger\right)^2 + g_3(t)\left(\hat{a} + \hat{a}^\dagger\right)^3 + g_4(t)\left(\hat{a} + \hat{a}^\dagger\right)^4$$

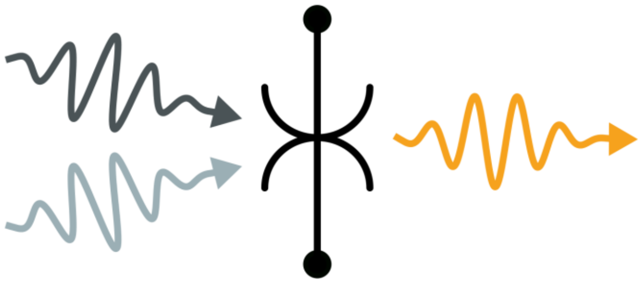


Nonlinear Elements	Flux pump	Charge pump

Desired Potential	Resonant Control

Available Gates

Gates are activated by external drives.



Displacement

$$\hat{D}(\alpha) = \exp\left(\alpha \hat{a}^\dagger - \alpha^* \hat{a}\right)$$

Squeezing

$$\hat{S}(\xi) = \exp\left(\frac{\xi}{2}\hat{a}^2 - \frac{\xi^*}{2}\hat{a}^{\dagger 2}\right)$$

Rotations

$$\hat{R}(\theta) = \exp\left(-i\theta \hat{a}^\dagger \hat{a}\right)$$

Cubic Phase Gate

$$\hat{\Gamma}(\gamma) = \exp\left(i\gamma \hat{x}^3\right)$$

PREPARATION OF CUBIC PHASE STATE