Generating Robust Control Protocols for Quantum Dot Spin Qubits

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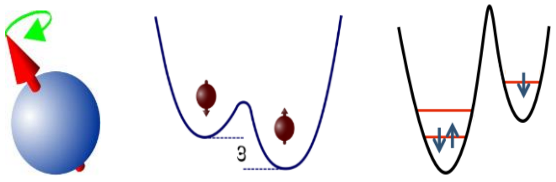
Abstract

Electron spins in semiconductor quantum dots are promising platforms for quantum computing due to their long coherence times and potential scalability. The main challenge in realizing a practical quantum computer in these systems is combating the effects of noise. Although techniques based on the theory of dynamical error suppression are often employed to mitigate the effects of noise, they are not effective against noise which vary significantly during the qubit evolution. This issue can potentially be resolved by using geometric quantum gates to evolve qubits, which are conjectured to be insensitive against such high-frequency noise. Therefore, our general research goal is to combine the theory of dynamical error suppression with geometric quantum computation. This approach can potentially mitigate a spectrum of noise frequencies wider than what is achievable with existing control protocols and allow generation of one- and two-qubit gates with fidelities well above the fault-tolerant threshold.

Quantum Computing with Spins

Why use spin qubits?

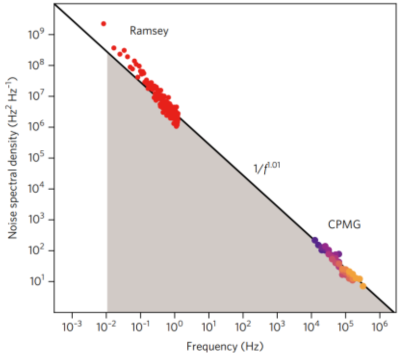
- High-precision electron traps using quantum dots
- Long coherence times ($\sim 10\mu s$ to $\sim 1ms$)



Examples of qubits made with spin(s)

What are the challenges?

- Very susceptible to charge noise
- Imagine having electrons hop around impurity sites / defects on your silicon device



Noise power spectral density of charge noise

Dealing with low-frequency noise

We can use techniques based on the theory of dynamical error suppression to mitigate the effects of low-frequency noise.

Try composite pulse sequences!

Key idea: noisy gates are cleverly arranged so that their errors cancel one another.

- If the noise is slow compared to the qubit dynamics, the accumulated noise in each noisy gate should be roughly equal
- One can try pair-wise cancellation of error

Suppose we have a noisy entangling gate

$$U(t) = \exp\left[-\imath\frac{\theta}{2}\sigma_{ZZ}\right](I + \imath\delta_{ZI}\sigma_{ZI})$$

We want to eliminate the δ_{ZI} error term.

Try using simultaneous π rotations about the X-axis of both qubits (σ_{XX})

$$U(t)\sigma_{XX}U(t)\sigma_{XX} = \exp\left[-\imath\frac{2\theta}{2}\sigma_{ZZ}\right](I + \imath\delta_{ZI}\sigma_{ZI})(I - \imath\delta_{ZI}\sigma_{ZI})$$
$$= \exp\left[-\imath\frac{2\theta}{2}\sigma_{ZZ}\right](I + \mathcal{O}(\delta^2))$$

Pros: well-established theory and works very well

Cons: useless against high-frequency noise

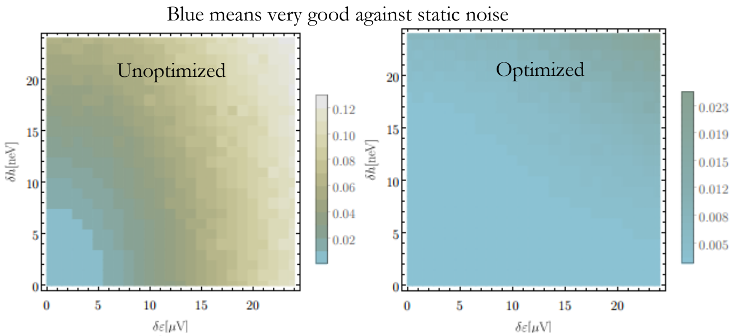
Composite Pulses in Action

Singlet-triplet spin qubits

Experimental parameter optimization with composite pulses

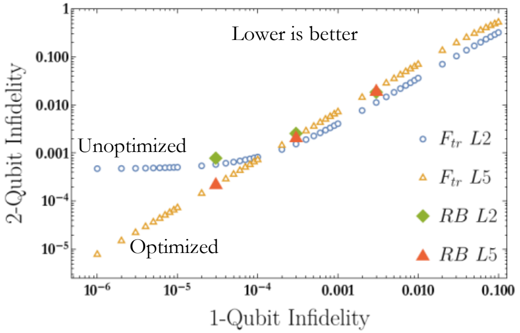
Average CPHASE fidelity comparison

Sequence	$\langle F\rangle_{unoptimized}$	$\langle F\rangle_{optimized}$
No refocusing	.768	.811
Singly refocused	.950	.974
Doubly refocused	.944	.996



Superconducting transmon qubits

We also aim to develop general optimal control protocols that can be applied in many other systems.



Future topics

We want minimize the effects of high-frequency noise as well

- Try using geometric quantum gates (phase is proportional to enclosed area by evolution path)
- Conjectured to have high-frequency robustness
- If high-frequency noise is weak, the fluctuations average out and preserve the overall area and phase

Our overall goal is to combine the concepts of dynamical error suppression with geometric quantum gating to generate quantum gates that can mitigate a very wide spectrum of noise frequencies.