Simple quantum feedback of a solid-state qubit

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We propose an experiment on quantum feedback control of a solid-state qubit, which is almost within the reach of the present-day technology. Similar to the earlier proposal, the feedback loop is used to maintain the coherent oscillations in a qubit for an arbitrary long time; however, this is done in a significantly simpler way, which requires much smaller bandwidth of the control circuitry.

The main idea is to use the quadrature components of the noisy detector current to monitor approximately the phase of qubit oscillations. The price for simplicity is a less-than-ideal operation: the fidelity is limited by about 95%. The feedback loop operation can be experimentally verified by appearance of a positive in-phase component of the detector current relative to an external oscillating signal used for synchronization.

cond-mat/0404696

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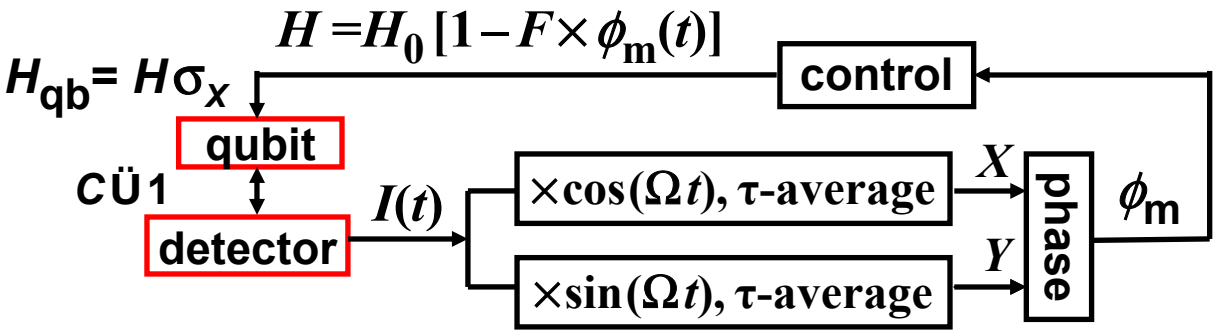


We want to maintain coherent (Rabi) oscillations for arbitrary long time,
$\rho_{11}-\rho_{22}=\cos(\Omega t)$, $\rho_{12}=i\sin(\Omega t)/2$

Idea: **use two quadrature components of the detector current $I(t)$ to monitor approximately the phase of qubit oscillations**
(a very natural way for usual classical feedback!)

$$X(t) = \int_{-\infty}^{t} [I(t') - I_0] \cos(\Omega t') \exp[-(t-t')/\tau]\, dt$$
$$Y(t) = \int_{-\infty}^{t} [I(t') - I_0] \sin(\Omega t') \exp[-(t-t')/\tau]\, dt$$

$$\phi_m = -\arctan(Y/X)$$

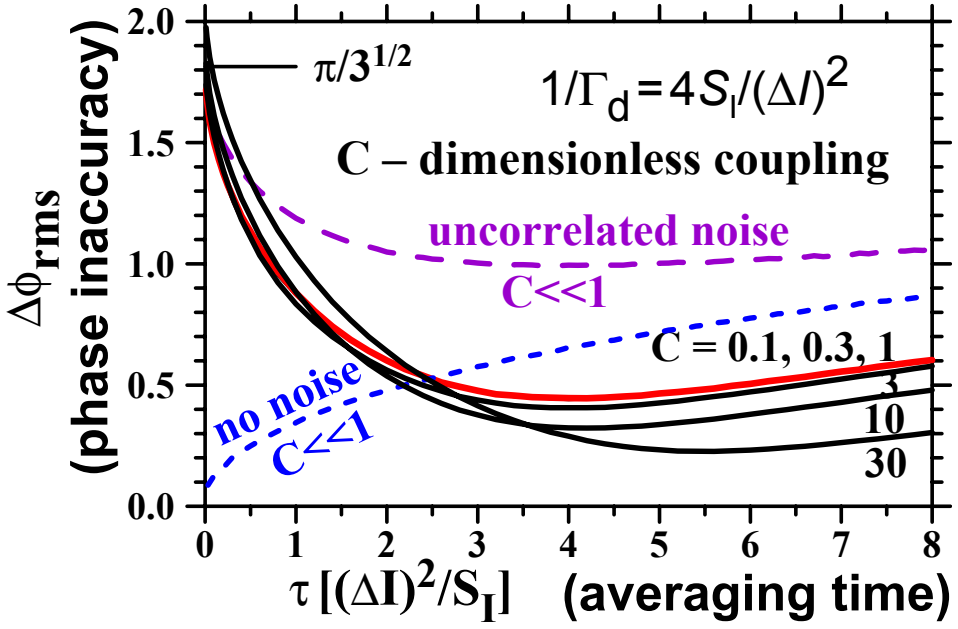
(similar formulas for a tank circuit instead of mixing with local oscillator)

Advantage: **simplicity and relatively narrow bandwidth** $(1/\tau \sim \Gamma_d \ll \Omega)$

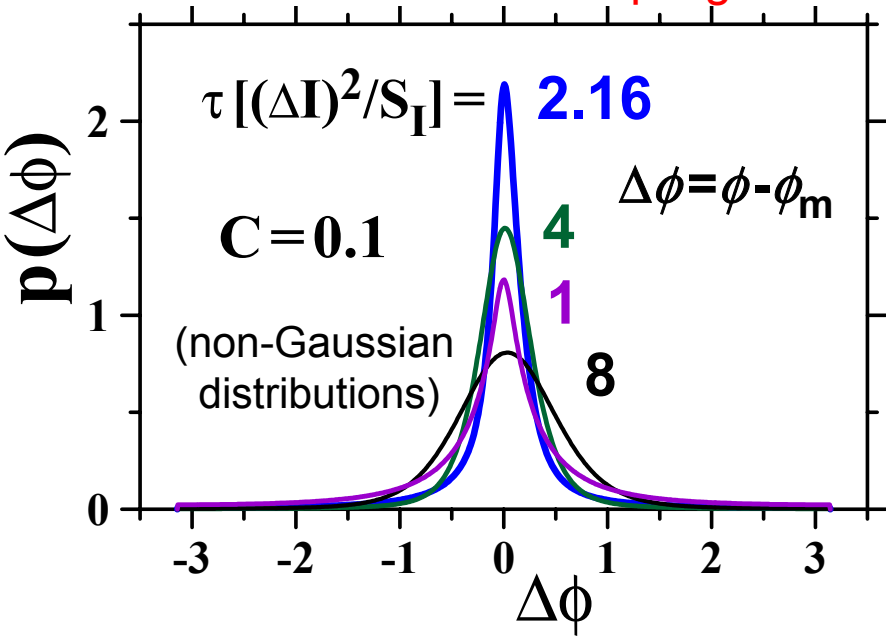
Anticipated problem: without feedback the spectral peak-to-pedestal ratio <4, therefore not much information in quadratures

(surprisingly, situation is much better than anticipated!)

Accuracy of phase monitoring via quadratures (no feedback yet)



weak coupling C á 1



Noise improves the monitoring accuracy!

(purely quantum effect, "reality follows observations")

Best approximation

$\langle X^2+Y^2\rangle=(S_I/\Delta I)^2$

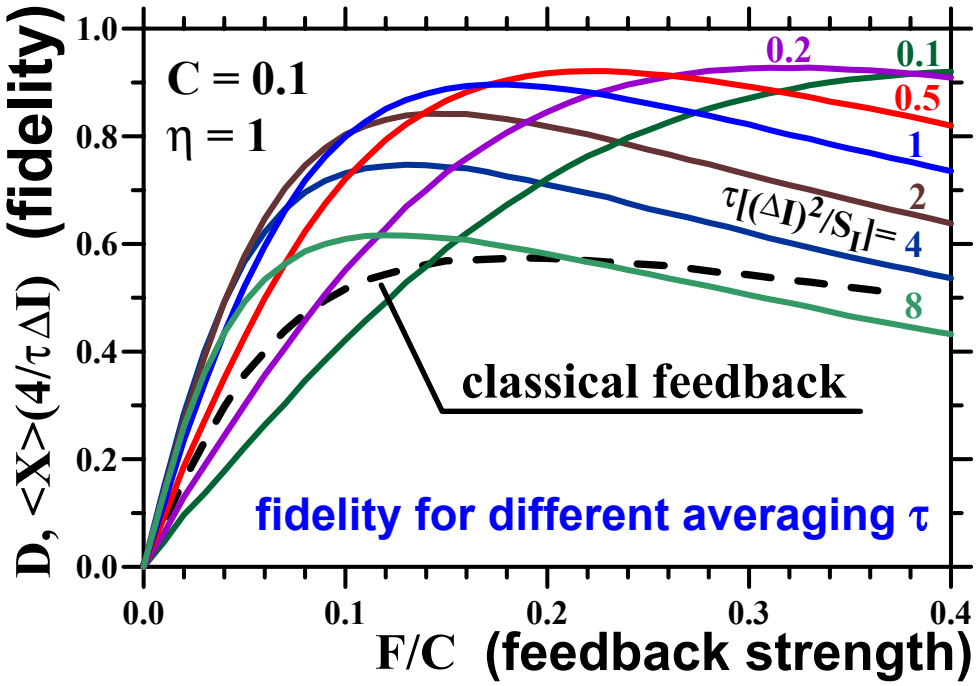
$(2/5)(41^{1/2}-1)\approx 2.16$

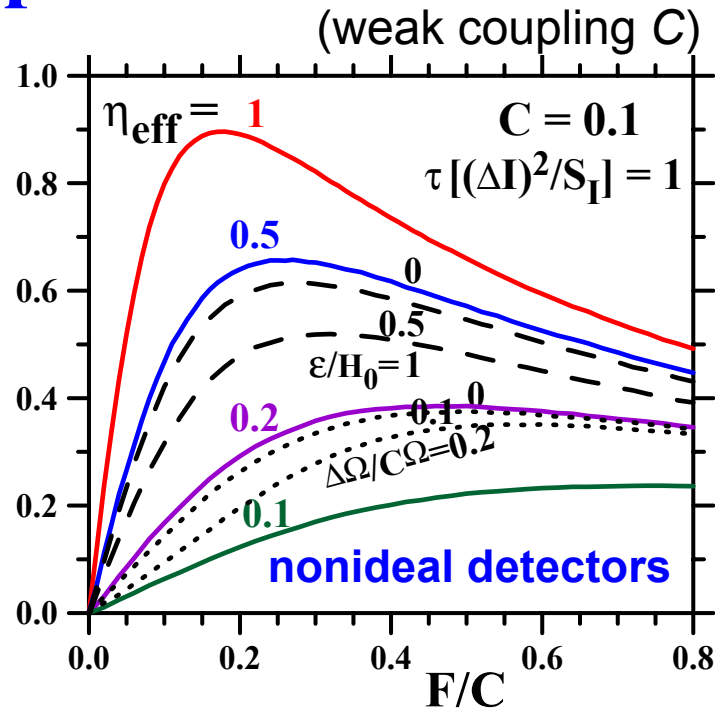
$$d\phi/dt = -[I(t)-I_0]\sin(\Omega t+\phi)(\Delta I/S_I)$$ (actual phase shift, ideal detector)

$$d\phi_m/dt = -[I(t)-I_0]\sin(\Omega t+\phi_m)/(X^2+Y^2)^{1/2}$$ (observed phase shift)

Noise enters the actual and observed phase evolution in a similar way

Quantum feedback performance





- Fidelity F up to ~95% achievable (D~90%)
- Natural, practically classical feedback setup
- Averaging $\tau \sim 1/\Gamma >> 1/\Omega$ (narrow bandwidth!)
- Detector efficiency (ideality) $\eta \le 0.1$ still OK
- Robust to asymmetry ε and frequency shift $\Delta\Omega$
- Very simple verification – just positive in-phase quadrature $\langle X \rangle$

$$D \equiv 2F - 1$$

$$F \equiv \langle \mathrm{Tr}\, \rho(t)\, \rho_{des}(t) \rangle$$

$$D \simeq \langle X \rangle (4/\tau \Delta I)$$

X – in-phase quadrature of the detector current

Simple experiment?!

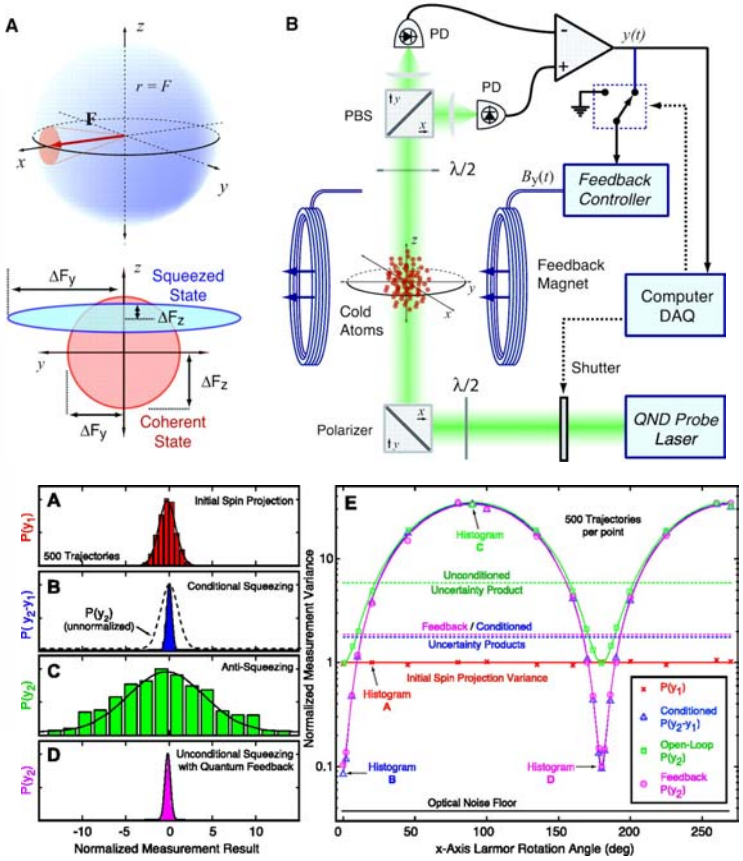
Quantum feedback in optics

Recent experiment: Science 304, 270 (2004)

Real-Time Quantum Feedback Control of Atomic Spin-Squeezing

JM Geremia,* John K. Stockton, Hideo Mabuchi

Real-time feedback performed during a quantum nondemolition measurement of atomic spin-angular momentum allowed us to influence the quantum statistics of the measurement outcome. We showed that it is possible to harness measurement backaction as a form of actuation in quantum control, and thus we describe a valuable tool for quantum information science. Our feedback-mediated procedure generates spin-squeezing, for which the reduction in quantum uncertainty and resulting atomic entanglement are not conditioned on the measurement outcome.



First detailed theory:

H.M. Wiseman and G. J. Milburn,
Phys. Rev. Lett. 70, 548 (**1993**)

No experimental attempts of quantum feedback in solid-state yet (even theory is still considered controversial)

Experiments soon?

Conclusions

- Very straightforward, practically classical feedback idea (monitoring the phase of oscillations via quadratures) works well for the qubit coherent oscillations
- Much simpler realization than for quantum feedback of Ruskov-Korotkov, Phys. Rev. B 66, 041401(R) (2002)
- Price for simplicity is a less-then-ideal operation (fidelity is limited by ~95%)
- Feedback performance is much better than expected
- Relatively simple experiment (simple setup, narrow bandwidth, inefficient detectors OK, simple verification)