Quantum noise eater for a single qubit

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Coherent quantum superposition

Coherent superposition of quantum states:

- $|0\rangle + e^{i\theta}|1\rangle$
- Plays a crucial role in quantum information protocols
- Manifested in quantum interferometric experiments

What is it good for? Superposition is a resource for various quantum information tasks

- Quantum key distribution
- Quantum computing
- Quantum imaging

Mechanisms of decoherence

Many systems cannot preserve the superposition for long time $\rightarrow$ Decoherence

- Fluctuation of macroscopic physical parameters $\rightarrow$ dephasing:
  $|0\rangle\langle 0| + |1\rangle\langle 1| + e^{i2\theta}|0\rangle\langle 1| + e^{-i2\theta}|1\rangle\langle 0| \rightarrow N(\mu, \sigma)$:
  $|0\rangle\langle 0| + |1\rangle\langle 1| + e^{i2\mu - 2\sigma^2}|0\rangle\langle 1| + e^{-i2\mu - 2\sigma^2}|1\rangle\langle 0|$
- Coupling between system and environment: entanglement is present, Zurek's einselection
- Mixing the system with some other system representing noise - e.g. qubit transforms to a system with higher dimension when coherently mixed with another qubit

Trouble with coherent noise

Simplified theoretical calculations:

Qubit resource

- $[|0\rangle + \exp(i\varphi)\,|1\rangle]/\sqrt{2}$
- dual-rail enc: $|\Psi\rangle_{AB} = [|1,0\rangle_{AB} + \exp(i\varphi)\,|0,1\rangle_{AB}]/\sqrt{2}$
- Perfect resource for further quant inf processing
- Evaluation of the resource by visibility V
- $V = 1$

Adding "noise" photon to the signal mode B

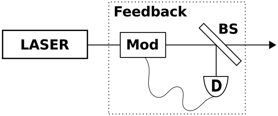
$a_B^\dagger|\Psi\rangle_{AB} = |\Psi'\rangle_{AB} = [|1,1\rangle_{AB} + \sqrt{2}\exp(i\varphi)\,|0,2\rangle_{AB}]/\sqrt{3}$
State fully coherent but may cause errors in further processing

$$V = \frac{2}{3}$$

Noise eater technique

Laser noise eater = reducing amplitude noise

- Partial measurement of laser light
- Feedback controller with modulation



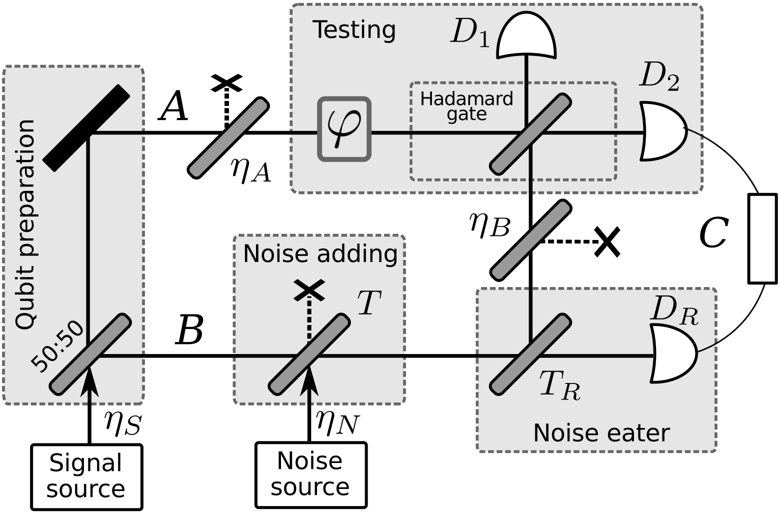
Qubit noise eater: subtract one photon

$a_B|\Psi'\rangle_{AB}$ ending up with state
$|\Psi''\rangle_{AB} = [|1,0\rangle_{AB} + 2\exp(i\varphi)\,|0,1\rangle_{AB}]/\sqrt{5}$

When mode B is properly attenuated

$$V = 1$$

Scheme of the interference experiment



Theor. results without noise eater

Probability to detect at least one photon at D_1

$$P = \frac{\eta_D}{4}\left(W_1 + W_2 \cos\varphi\right),$$

$W_1 = 2\,\eta_N\eta_B + \eta_S\eta_A + \eta_S\eta_N\eta_B T\eta_D\eta_A - 2\,\eta_N\eta_B T - \eta_S\eta_N{\eta_B}^2\eta_D T + \eta_S\eta_B T - \eta_S\eta_N\eta_B\eta_D\eta_A + \eta_S\eta_N{\eta_B}^2 T^2\eta_D$

$W_2 = 2\,\eta_S\eta_N{\eta_B}^{3/2}\eta_D\sqrt{T}\sqrt{\eta_A} - 2\,\eta_S\eta_N{\eta_B}^{3/2} T^{3/2}\eta_D\sqrt{\eta_A} - 2\,\eta_S\sqrt{T}\sqrt{\eta_A}\sqrt{\eta_B}$

$V = (P_{\max} - P_{\min})/(P_{\max} + P_{\min})$

$$V = \frac{\eta_S T(\eta_B\eta_N T\eta_D - \eta_B\eta_N\eta_D + 1)}{\eta_B\eta_S\eta_N\eta_D T(T-1) + \eta_S T + \eta_N(1-T)}$$

where we used $\eta_A = \eta_B T$.

Theor. results without noise eater

Our proof-of-principle experiment:

- equal input signal and noise losses $\eta_S = \eta_N$
- detector efficiency $\eta_D = 0.5$

$$V = \frac{2T + \eta_B \eta_S T(T-1)}{2 + \eta_B \eta_S T(T-1)}.$$

For typical $\eta_S = \eta_N \ll 1$,

$$V \approx T$$

Theor. results with noise eater

Quantum noise eater for qubit

Beamsplitter and single photon detector, probabilistic photon subtraction, postselection: coincidence detection

$$P_c(\varphi) = \frac{1}{4}\eta_S\eta_N T_R\eta_D\eta_R(1-T)(\eta_A + 4\eta_B T(1-T_R) - 4\cos(\varphi)\sqrt{\eta_A\eta_B T(1-T_R)}).$$

$\eta_A = \eta_B T$

$$V = \frac{4\sqrt{1-T_R}}{5-4T_R}$$

$T_R = 3/4$

$$V = 1$$

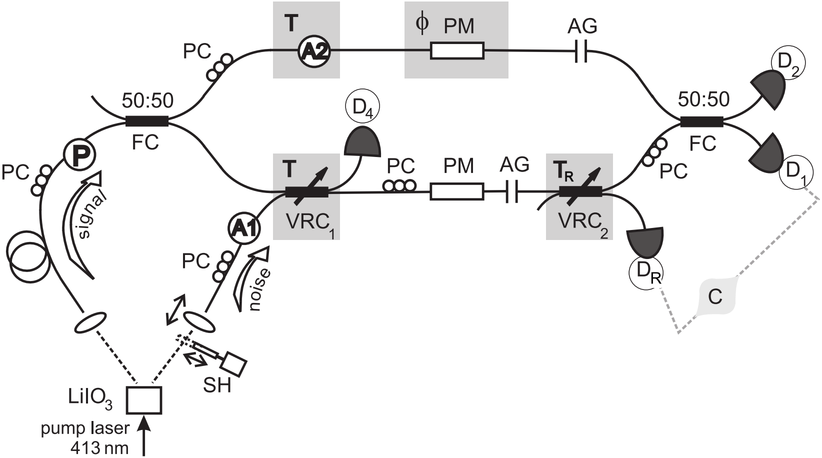
Experimental realization

- Photons in fibre-optics two-photon Mach-Zehnder interferometer
- Signal and noise photon generated in SPDC process type I, pumping at 413 nm, LiIO3 crystal
- Noise photon coherently added to the signal photon

Theory & experiment

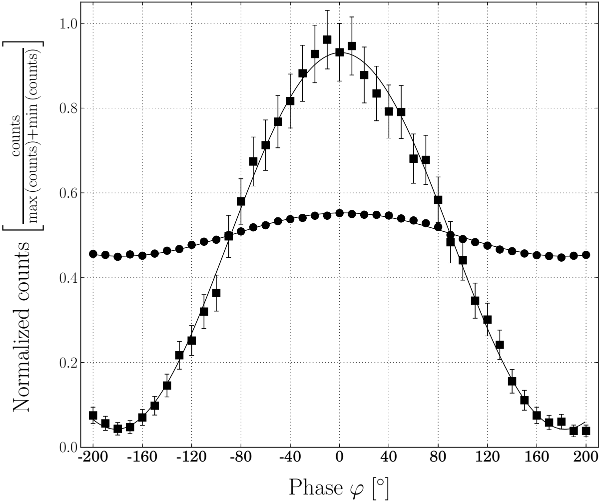
M. Gavenda, L. Čelechovská, M. Dušek and R. Filip, Quantum noise eater for a single qubit, submitted to New Journal of Physics

Experimental setup

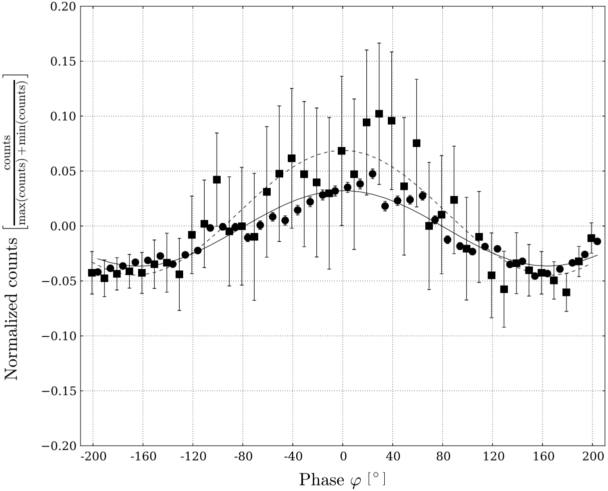


Exp results - int. fringes for $T = 0.109$

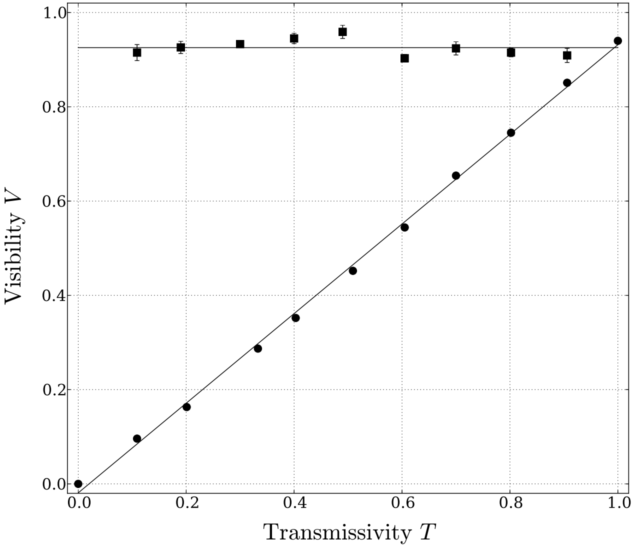
$V = 0.097 \rightarrow V = 0.915$



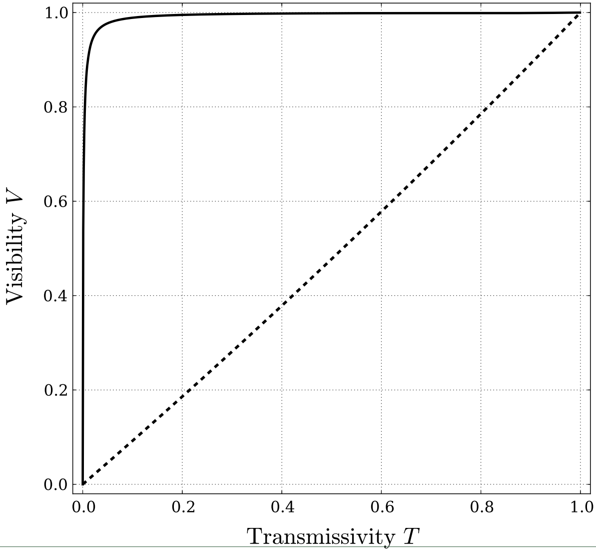
Exp results - difference of int. fringes for $T = 0.109$



Exp results - visibility



Numerical results - two-photon noise



Summary & Outlook

1. Coherent noise can be harmful for qubit superposition.
2. We have proposed and experimentally demonstrated an elementary quantum noise eater that recovers the resource
3. Numerical results for two-photon noise presented
4. Extensions to partially coherent noise, usage of spectral filtering to induce coherence