Experimental characterization of photon-number noise in Rarity-Tapster-Loudon-type interferometers

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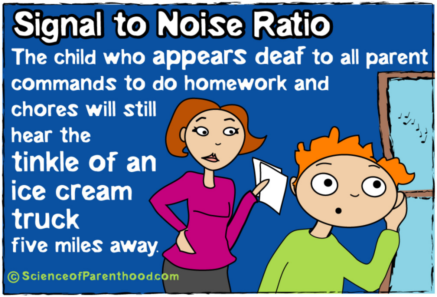
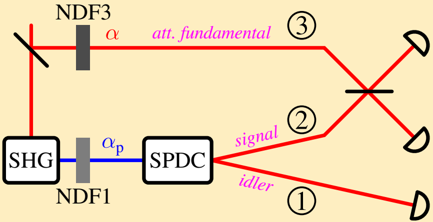


Motivation

Rarity-Tapster-Loudon type interferometer J. Opt. B **7**, S171 (2005)



Quantum teleportation

- entanglement swapping
- quantum relays
- quantum computing
- cluster states
- ...

Visibility of Hong-Ou-Mandel bunching

- polarization, frequency, spatial mode
- arrival time jitter
- noise caused by additional photons

Spontaneous parametric down-conversion

Hamiltonian

$$\hat{H} = \imath\hbar\chi^{(2)}\left(\alpha_p^*\hat{a}_1\hat{a}_2 - \alpha_p\hat{a}_1^\dagger\hat{a}_2^\dagger\right) = \gamma\alpha_p\hat{a}_1^\dagger\hat{a}_2^\dagger + H.C.$$

α_p – pumping amplitude ($\gg$), γ – interaction constant ($\ll$)

Output state

$$|\psi_s\rangle \propto |00\rangle + \kappa|11\rangle + \frac{\kappa^2}{2}|22\rangle + \cdots, \qquad |\kappa| = |\imath t\gamma\alpha_p/\hbar| \ll 1$$

Coupling into the fibers with efficiencies $t_{1,2} \ll 1$

$$\underbrace{|00\rangle}_{omitted} + \kappa t_1 t_2|11\rangle + \kappa t_1\underbrace{\sqrt{1-t_2^2}}_{\approx 1}|10\rangle + \frac{\kappa^2}{2}t_1\underbrace{\sqrt{1-t_1^2}}_{\approx 1}t_2^2|12\rangle + \underbrace{\frac{\kappa^2}{2}t_1^2t_2^2|22\rangle}_{neglected}$$

Attenuated fundamental mode

Coherent state

$$|\alpha\rangle = \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

Coupled state

- amplitude α includes all losses and coupling efficiency
- number of terms of expansion $\sim$ the accuracy of the model

$$|\alpha\rangle \approx |0\rangle + \alpha|1\rangle + \frac{\alpha^2}{\sqrt{2}}|2\rangle + \frac{\alpha^3}{\sqrt{6}}|3\rangle$$

Signal vs. Noise

Wanted signal

state $|111\rangle$

$$CC_g \approx |\kappa|^2 t_1^2 t_2^2 |\alpha|^2$$

Noise from SPDC

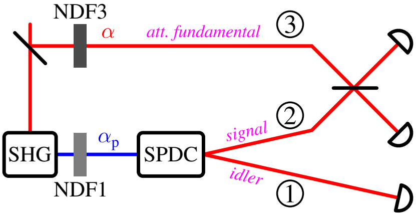
state $|120\rangle$

$$CC_s \approx |\kappa|^4 t_1^2 t_2^4 / 4$$

Noise from att. fundamental

state $|102\rangle$ and $|103\rangle$

$$CC_f \approx |\kappa|^2 t_1^2 \left(|\alpha|^4/2 + |\alpha|^6/6 \right)$$



Signal to Noise Ratio

$$\mathrm{SNR} \equiv \frac{CC_g}{CC_s + CC_f} =$$

$$= \frac{12|\alpha|^2 t_2^2}{3|\kappa|^2 t_2^2 + 6|\alpha|^4 + 2|\alpha|^6}$$

Dependence of SNR

$$R \equiv \frac{CC_f}{CC_s} = \frac{2|\alpha|^4}{|\kappa|^2 t_2^2} + \frac{2|\alpha|^6}{3|\kappa|^2 t_2^4} \approx \frac{2|\alpha|^4}{|\kappa|^2 t_2^2} \quad \rightarrow \quad \mathrm{SNR} \approx \frac{2\sqrt{2R}}{|\kappa|(R+1)}$$

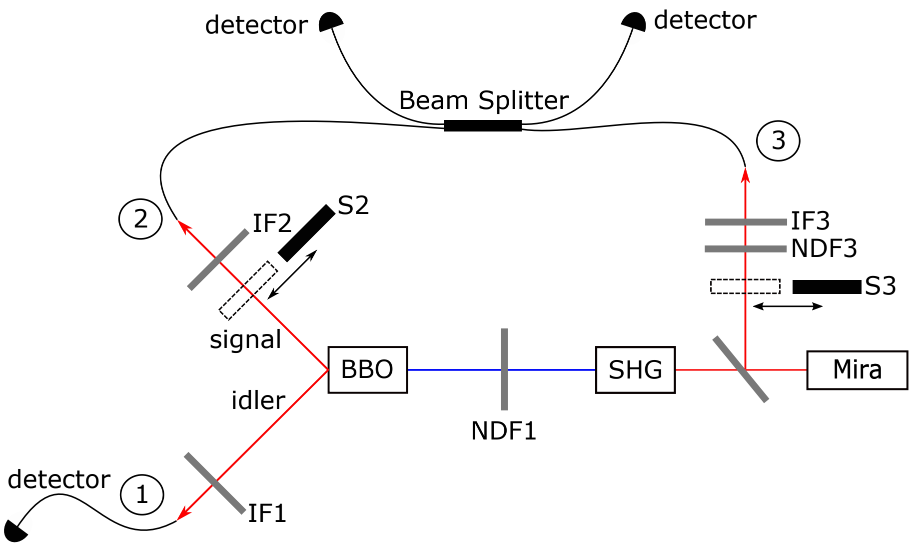
- maximal SNR for $R = 1$ ($CC_f = CC_s$)
- for larger $|\alpha|$ approximation is no longer valid $\rightarrow R < 1$

$$R \approx 1 \quad \rightarrow \quad \mathrm{SNR} \propto \sqrt[3]{\frac{16 t_1^2 t_2^4}{CC_g}}$$

better SNR

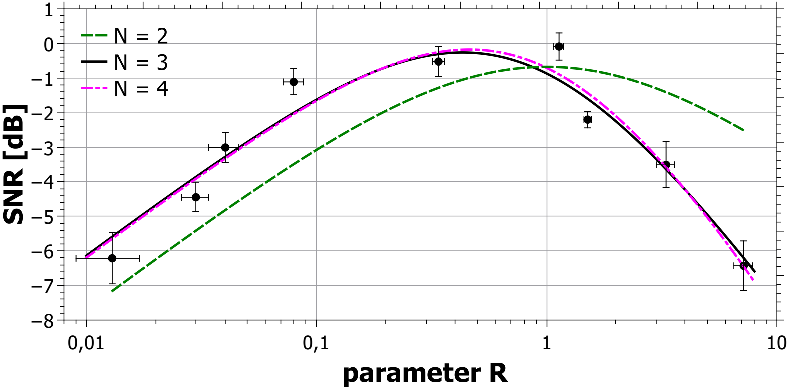
- by decreasing $|\kappa|$ ($|\alpha_p|$)
- by optimizing coupling efficiency t_1 and t_2

Experimental setup



Dependence of SNR on fraction R

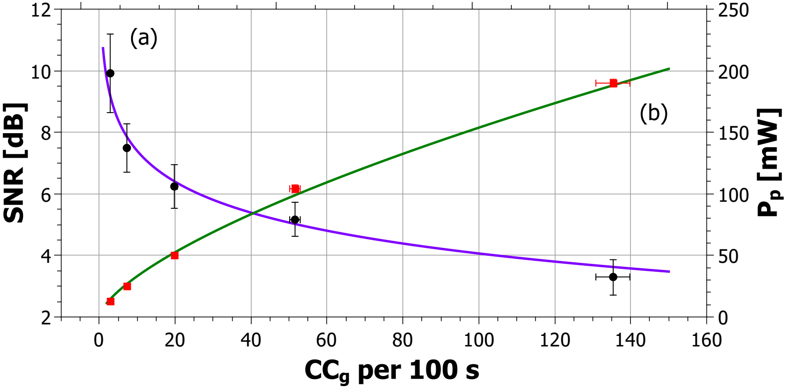
$R = CC_f/CC_s$ is changed by attenuating fundamental mode (NDF3)



$$\mathrm{SNR} \approx \frac{2\sqrt{2R}}{|\kappa|(R+1)} \qquad |\alpha\rangle \approx |0\rangle + \alpha|1\rangle + \frac{\alpha^2}{\sqrt{2}}|2\rangle + \frac{\alpha^3}{\sqrt{6}}|3\rangle$$

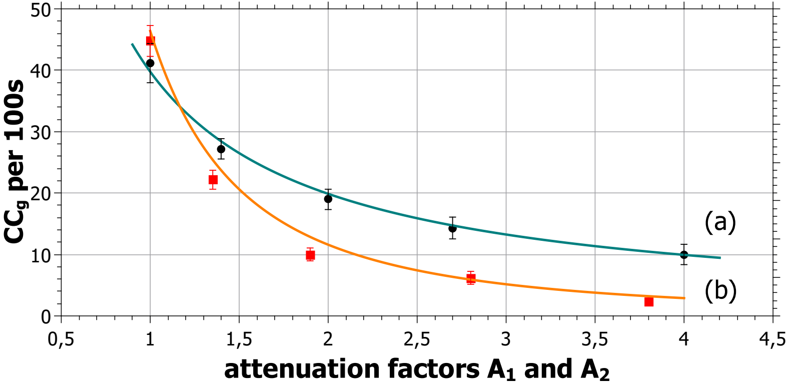
Dependence of SNR on CC_g

- theoretically SNR $\propto CC_g^{-1/3}$
- CC_g is changed by attenuating pump of SPDC (NDF1)
- NDF3 was set to have constant fraction $R \approx 0.35 \pm 0.04$

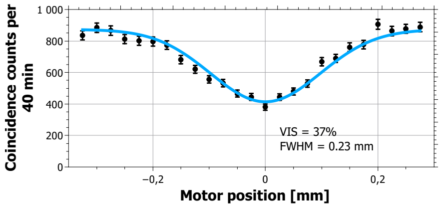


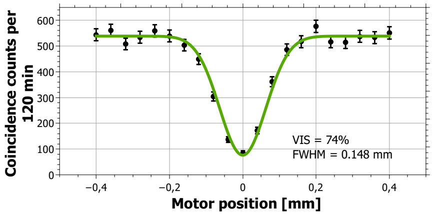
Dependence of CC_g on coupling efficiencies

- R and α_p are constant $\rightarrow$ SNR is constant $\sim$ 5 dB
- theoretically $CC_g \propto t_1^2 t_2^4$
- t_1 and t_2 are changed by closing diaphragm, $t^2 \rightarrow t^2/A$



Hong-Ou-Mandel interference

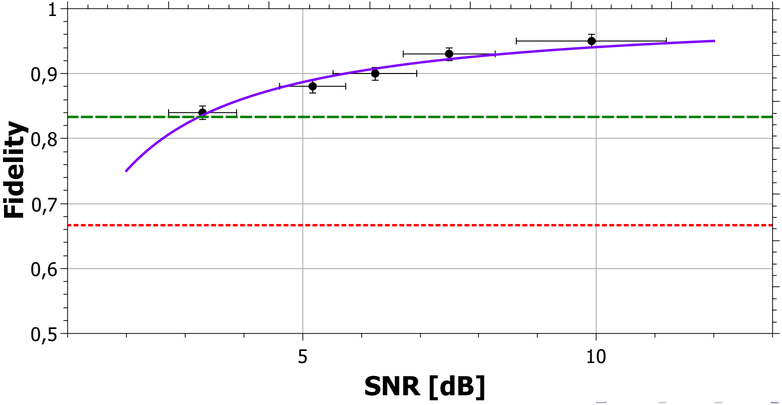




	P_p [mW]	$\mathrm{F}_{\mathrm{idler}}$	false ccc	ccc rate	V of dip
max signal	190	10 nm	44 %	22/min	37 %
$R \approx 1$ by NDF3	190	10 nm	28 %	13/min	45 %
$R \approx 1$, NDF1,3	63	3 nm	17 %	7.2/min	72 %
$R \approx 1$, NDF1,3	48	3 nm	12 %	4.5/min	74 %

Fidelity of teleportation

- $F = |\langle\psi_{in}|\hat{\rho}_{out}|\psi_{in}\rangle|$
- signal $\rightarrow F = 1$
- noise $\rightarrow F = 1/2$ (random projections onto Bell states)
- dependence fidelity on SNR for fixed $R \approx 0.35$



Conclusions

- our theoretical model fit well to experimental data
- we find optimal fraction between noises from attenuated fundamental and SPDC mode – $R \approx 1$
- we can reach better SNR by lowering rate of threefold coincidences
- for teleportation fidelity $F > 0.8$ SNR > 3 dB is sufficient
- more details in Phys. Rev. A **96**, 023847 (2017)

Thanks for your attention