Noiseless loss suppression in quantum optical communication

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Abstract

The range of current quantum communication systems is restricted to several tens of kilometers due to unavoidable losses in optical links. Losses may in principle be overcome by entanglement distilation and quantum repeaters. However, these techniques require processing many copies of entangled states and using quantum memories. Recently, noiseless quantum amplification of light has emerged as a promising tool for quantum optical communication. Here, we introduce a dual process called noiseless attenuation, which, combined with noiseless amplification, enables the conditional suppression of optical losses to an arbitrary extent without adding noise, hence keeping quantum coherence. The method is remarkably simple since it only requires single-mode operations. We experimentally demonstrate it in the subspace spanned by vacuum and single-photon states.

Noiseless amplification

Any deterministic phase-insensitive signal amplification is unavoidably accompanied by the addition of noise.

Heralded noiseless quantum amplifier: probabilistic operation, quantum filter modulating amplitudes of Fock states,

$$g^{\hat{n}}, \qquad g > 1$$

Noiseless amplification of coherent states,

$$g^{\hat{n}}|\alpha\rangle \propto |g\alpha\rangle$$

Noiseless amplification cannot be performed perfectly becuase operator $g^{\hat{n}}$ is unbounded. However, arbitrarily good approximations are achievable albeit with a correspondingly low probability.

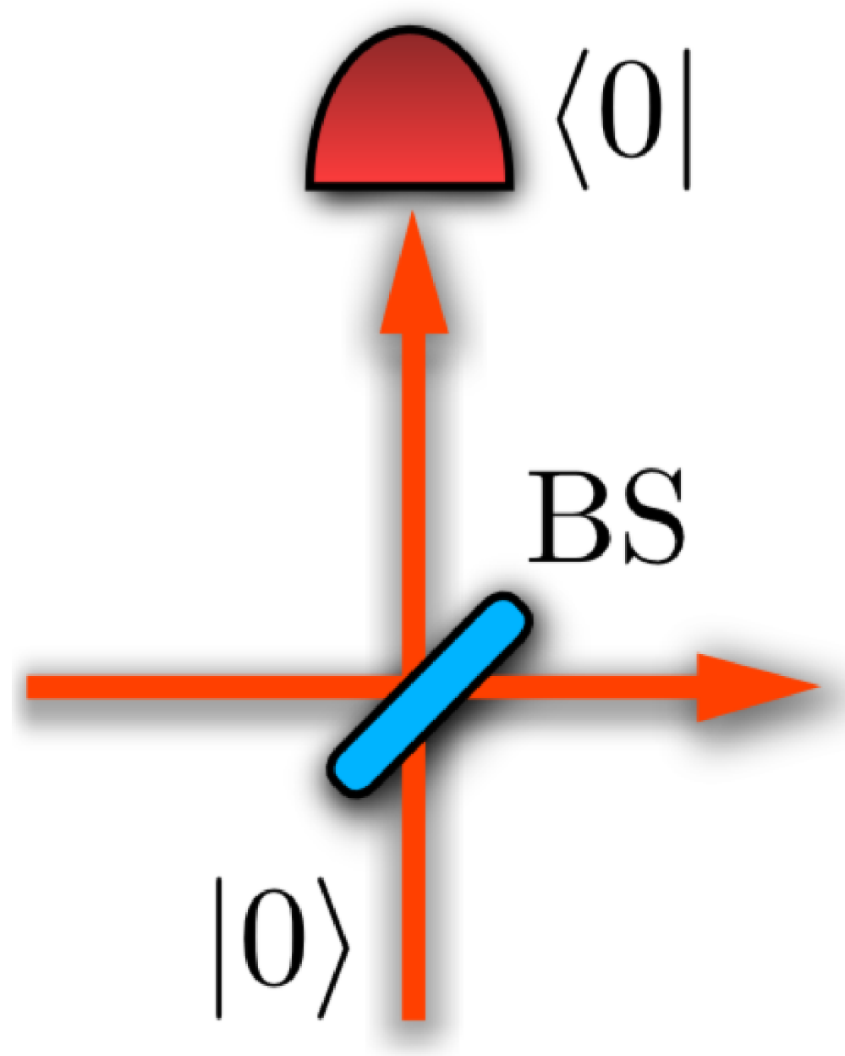
Possible implementations: photon addition and subtraction, multiphoton interference and single-photon detection.

Noiseless attenuation

Quantum filter diagonal in Fock basis:

$$\nu^{\hat{n}}, \qquad \nu < 1$$

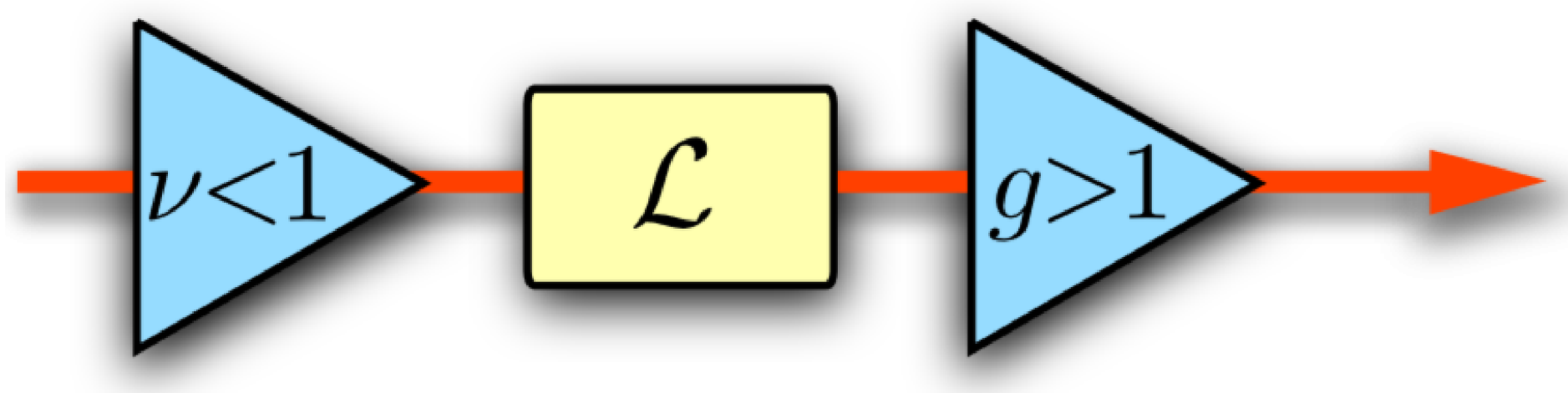
Attenuated state becomes closer to vacuum, but its purity and quantum coherence are preserved.



Possible implementation: beam splitter with amplitude transmittance $\nu < 1$ and a single-photon detector projecting on vacuum.

Noiseless loss suppression

- Lossy channel $\mathcal{L}$ with amplitude transmittance τ
- Noiseless attenuation before transmission
- Noiseless amplification at the output, $g = 1/(\nu\tau)$



Input pure superposition of vacuum and single-photon states

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle.$$

Mixed state at the output of a lossy channel:

$$\mathcal{L}(|\psi\rangle\langle\psi|) = |\tilde{\psi}\rangle\langle\tilde{\psi}| + (1-\tau^2)|c_1|^2|0\rangle\langle 0|,$$

where $|\tilde{\psi}\rangle = c_0|0\rangle + \tau c_1|1\rangle$.

Output of a lossy channel with noiseless attenuation at the input and noiseless amplification with gain $g = 1/(\nu\tau)$ at the output:

$$\rho_{\text{out}} \propto |\psi\rangle\langle\psi| + (1-\tau^2)\nu^2|c_1|^2|0\rangle\langle 0|.$$

In the limit $\nu \to 0$ losses are fully suppressed.

Channel tomography

Channel probed by one part of a maximally entangled single-photon state

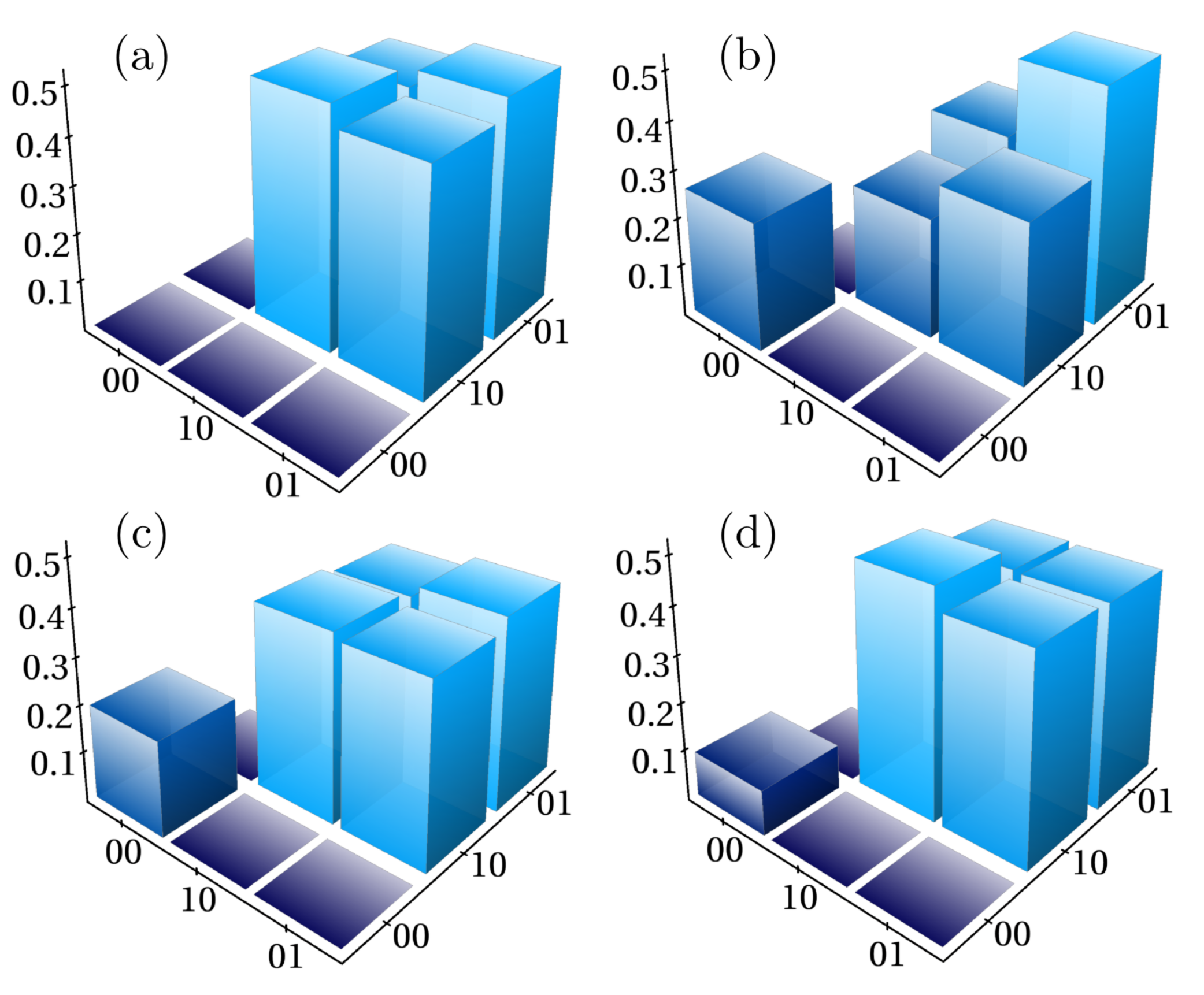
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)$$

Choi-Jamiolkowski isomorphism between lossy channel $\mathcal{L}$ and operator $\chi_{\mathcal{L}}$,

$$\chi_{\mathcal{L}} = \mathcal{I}_A \otimes \mathcal{L}_B(|\Psi\rangle\langle\Psi|).$$

Explicit $\chi_{\mathcal{L}}$ matrix of a lossy channel $\mathcal{L}$

$$\chi_{\mathcal{L}} = \frac{1-\tau^2}{2}|00\rangle\langle 00| + \frac{1}{2}(|01\rangle + \tau|10\rangle)(\langle 01| + \tau\langle 10|)$$

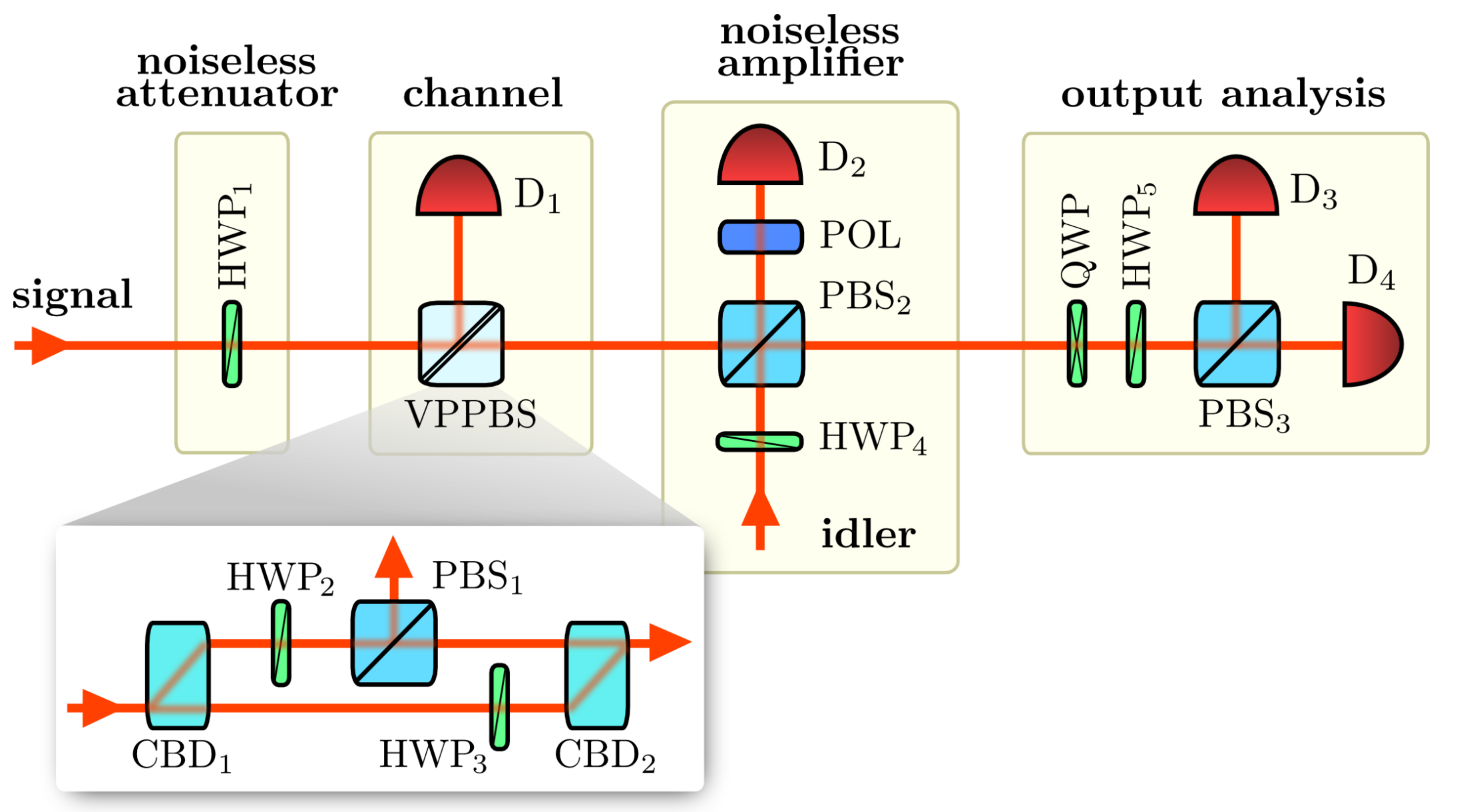


Experimentally determined $\chi_{\mathcal{L}}$ matrices:

(a) Identity channel.
(b) Lossy channel with $\tau = 1/\sqrt{2}$.
(c) Compensated lossy channel, $\nu = 1$, $g = \sqrt{2}$.
(d) Compensated lossy channel, $\nu = 1/\sqrt{2}$, $g = 2$.

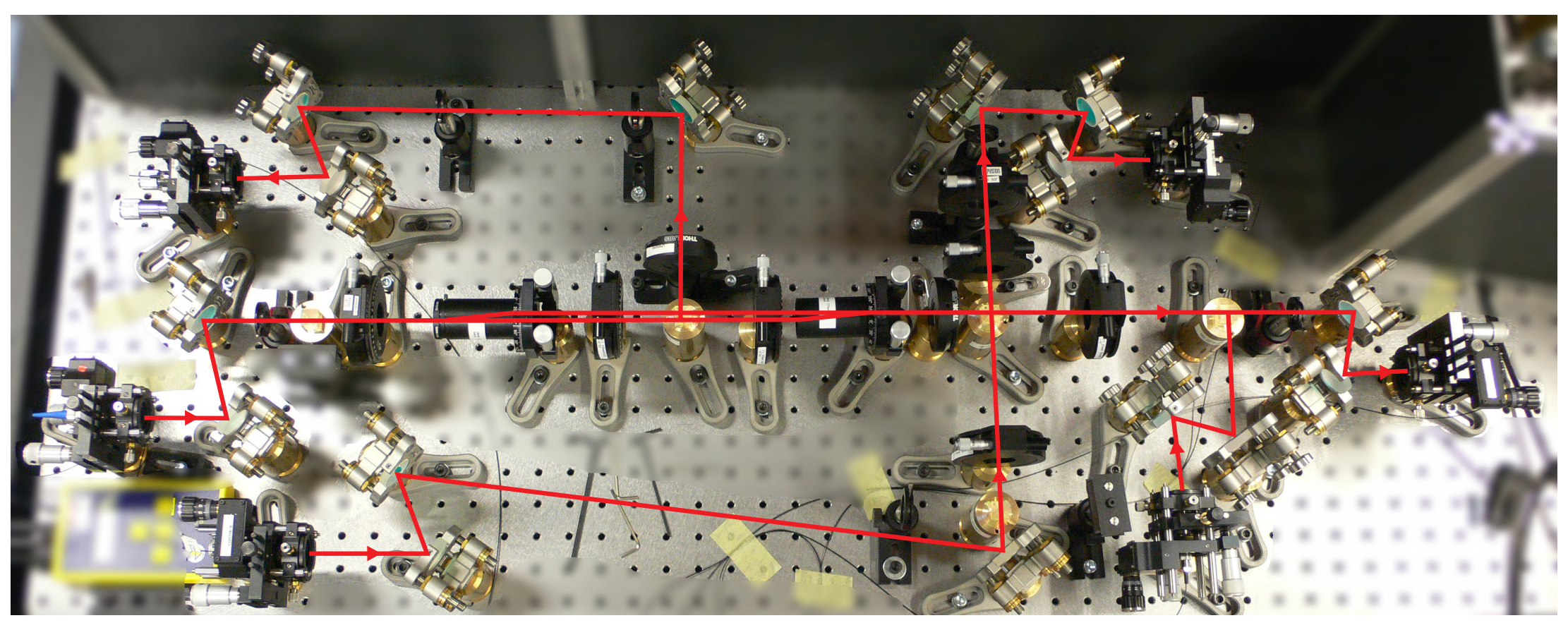
Experimental setup

Correlated photon pairs generated by SPDC are employed. Signal photon probes the lossy channel and idler photon drives the noiseless amplifier.



PBS – polarizing beam splitters, HWP – half-wave plates, QWP – quarter-wave plate, POL – polarizer, D$_j$ – single-photon detectors.

Variable partially polarizing beam splitter (VPPBS) is constructed from a pair of calcite beam displacers (CBD) and introduces tunable losses in the vertical polarization by rotation of HWP$_2$.



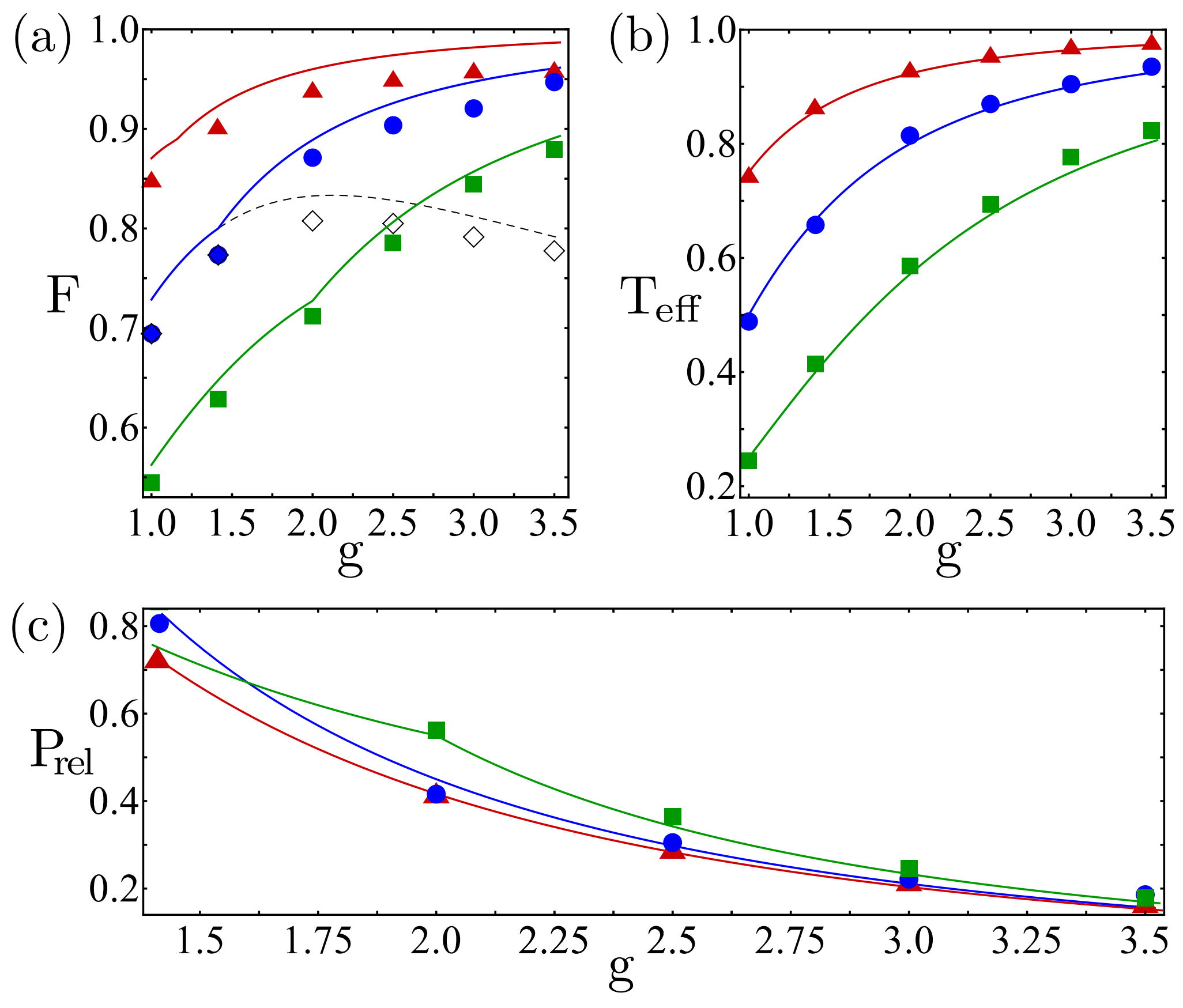
Protocol performance

Quantum channel fidelity

$$F = \langle\Psi|\chi_{\mathcal{L}}|\Psi\rangle.$$

Effective channel transmittance T_{eff}**:** conditional probability that a photon injected into the channel emerges at the output.

Relative success probability P_{rel}



- Experimental results for three levels of losses: $\tau^2 = 75\%$ (▲), $\tau^2 = 50\%$ (●) and $\tau^2 = 25\%$ (■).
- Solid lines indicate theoretical predictions.
- Noiseless attenuation $\nu = \min[1/(g\tau), 1]$.
- Diamonds provide channel fidelity for the case without noiseless attenuation ($\nu = 1$).

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