State comparison amplification of optical quantum coherent states

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Abstract

Quantum communication protocols, such as quantum key distribution [1] or quantum digital signatures [2], generally rely on the use of either single photon sources, or highly attenuated coherent sources. This requirement limits the maximum transmission distance that can be achieved, since a quantum channel can have a significant transmission loss when transmitting over 100's of kilometers in optical fiber.

This problem is not limited to quantum communication – the intensity of the transmitted light drops exponentially with transmission distance so conventional forms of communication are also affected. However, one major difference between the conventional and quantum communication is that conventional optical signals can be deterministically amplified to counteract the losses in the communication channel. Quantum communication protocols cannot simply attempt to overcome the losses by implementing conventional amplifiers since amplifying the quantum state will add deterministic noise to the quantum signal [4] [5]. To overcome the addition of excess noise during amplification, nondeterministic processes have been proposed [6]. These are probabilistic processes which work in post-selection [7–10].

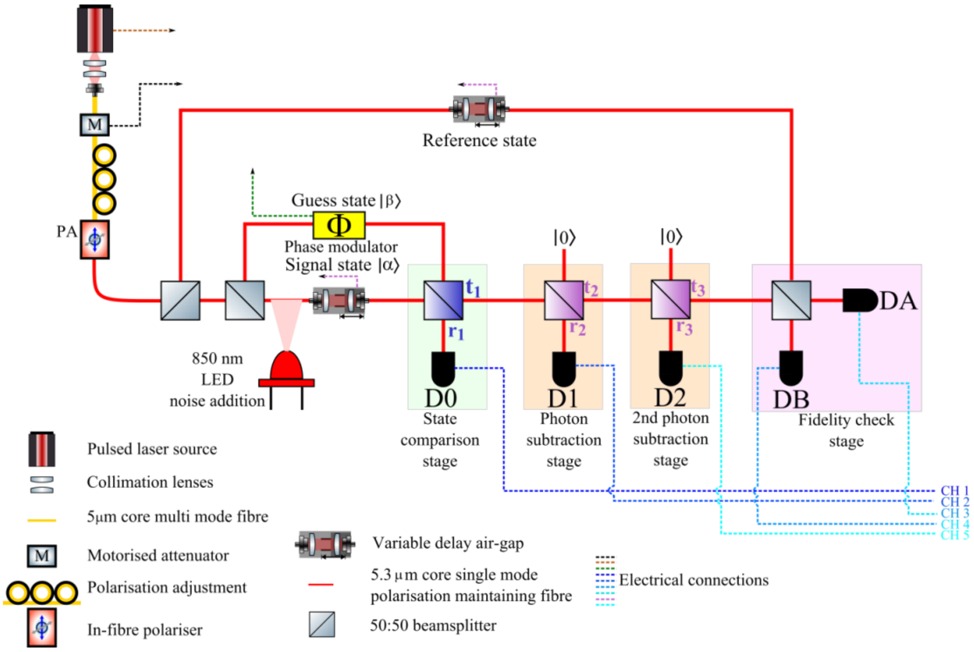

Figure 1 - State comparison amplification set-up, featuring one state comparison stage, two subtraction stages, and a tomography stage to test the fidelity of the amplified output.

State comparison amplification (SCAMP) is our chosen method of nondeterministic amplification where the post-selection conditions are based on two modular stages, a state comparison stage, and state subtraction stage [11]. The benefit over other amplification protocols is the use of coherent states (which originate from an attenuated laser source), and use of Geiger-mode single photon avalanche diode detectors (rather than photon number resolving detectors). Both of which are off-the-shelf components [12].

Figure 1 shows the experimental set-up for state comparison amplification. It features one state-comparison stage, and two photon-subtraction stages. The comparison stage compares the unknown signal state coming from sender Alice with a guess state, selected from the a-priori known phase-alphabet. If Alice's signal and the guess are the same, complete constructive interference occurs and the amplified state propagates through the rest of the amplifier device. If the guess is wrong, a portion of the coherent light intensity goes to the detector. If we discover that this happens, we know the guess is wrong, therefore one of our post-selective conditions is "no event" at the state comparison stage. The subtraction stages are highly transmitting (low reflectivity) beamsplitters which subtract a small intensity from the amplified state. In post-selection the output is conditioned as being accepted given one or more subtraction detection event(s). These subtraction stages increase the output fidelity of the amplifier device because there is a higher probability of a correctly guessed state triggering these stages than for an incorrectly guessed state. Having more than one of the subtraction stages increases this probability difference further.

As well as showing how post-selection conditions improve the amplified output, we have also tested the device against additional background noise, simulating ambient noise from a quantum channel or a single-photon detector with a higher dark count rate. The noise was inserted via a light emitting diode (LED), as shown in Figure 1.

When characterizing the state comparison amplifier two properties are useful; the output state fidelity, and correct state fraction. The fidelity refers to the overlap of the amplified state, to a reference state which is a perfectly-amplified version of the original signal. The correct state fraction is the portion of amplified states that correspond to correct guesses at the comparison stage and are actually the correctly amplified state. As the mean photon number ($|\alpha|^2$) increases the probability of a wrong guess triggering the state comparison detector will increase, the probability of the state subtraction triggering for a correct will also increase. The former will mean that fewer incorrect states will satisfy the post-selection conditions. The later will mean that correct state guesses will meet post-selection conditions more often. These lead to an increase in correct state fraction, and also fidelity.

Figure 2 shows the theoretical predictions for the fidelity and correct state fraction of the amplifier for two different post-selection conditions, and also two different phase alphabet sizes. The dashed lines show the prediction for post-selecting on the state comparison stage, and a single subtraction stage (two post-selection conditions). The solid lines show the prediction for post-selecting on the state comparison stage, and both state subtraction stages (three post-selection conditions).

In conclusion, we have successfully demonstrated a high fidelity, high output rate post-selecting non-deterministic amplifier operating on coherent states with amplitudes in the range 0 to 1.5 mean photons per pulse. We predict that this amplifier will see application in processes where coherent states with a limited phase alphabet are transmitted through a loss-inducing medium and where the trade-off of fidelity and rate is acceptable.

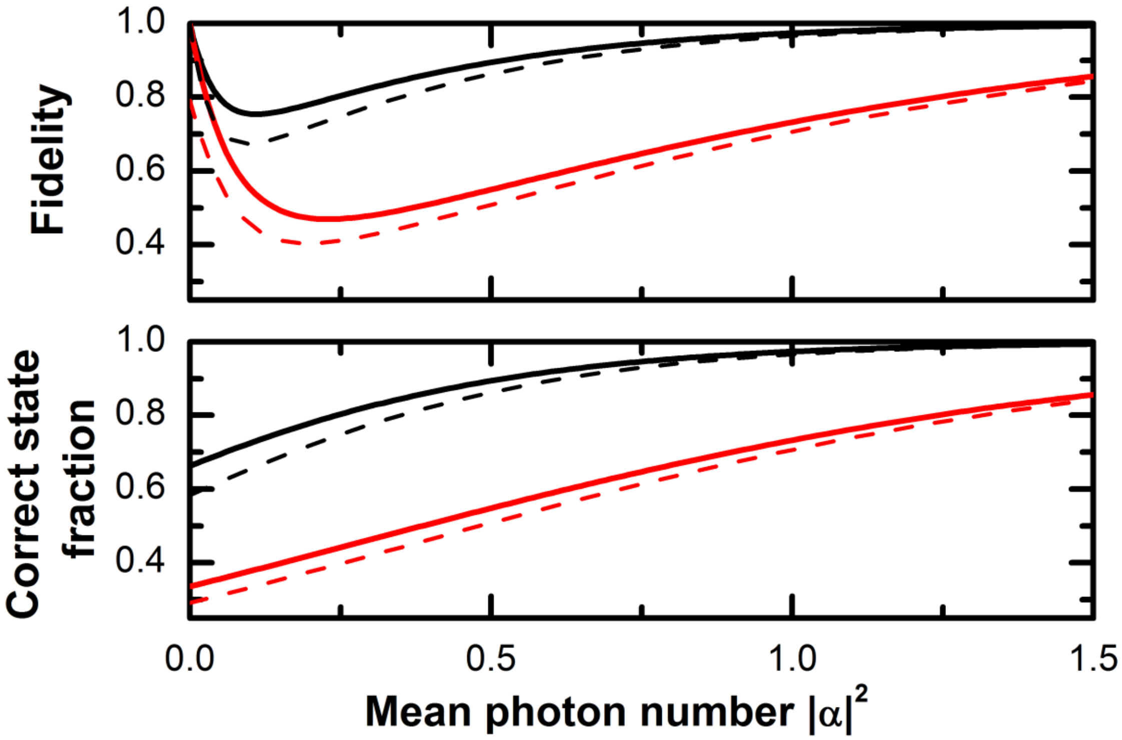

Figure 2 -The increase in fidelity and correct state fraction with an extra subtraction stage. The solid lines are the theory for the extra subtraction stage, while the dashed are for the single subtraction stage. Black is for a phase-alphabet size of 2, and red for 4.

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