Noiseless amplification of weak coherent fields without external energy

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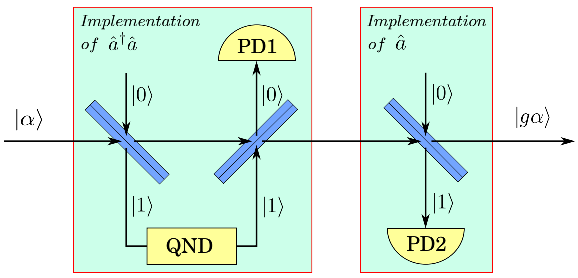
Introduction

According to the fundamental laws of quantum optics, noise is necessarily added to the system when one tries to clone or amplify a quantum state. However, it has recently been shown that the quantum noise related to the operation of a linear phase-insensitive amplifier can be avoided when the requirement of a deterministic operation is relaxed [1]. Nondeterministic noiseless linear amplifiers are therefore realizable. Usually nondeterministic amplifiers rely on using single photon sources [2]. We have, in contrast, studied an amplification scheme in which no external energy is added to the signal, but the energy required to amplify the signal originates from the stochastic fluctuations in the field itself [3].

Amplification scheme

- In previous works, operation $\hat{a}\hat{a}^\dagger$ has been shown to result in amplification of weak coherent fields [4].
- The use of an additional QND measurement adds a term $\hat{a}$ and removes the need to add photons from external single photon sources.
- Total operation implemented in the setup is $\hat{a}\hat{a}^\dagger\hat{a}$ which results in a field $|g\alpha\rangle$ on successful amplification.



Theory

- The calculations were performed in the Wigner function formalism and the effective gain and fidelity were used as figures of merit for the calculated output field of the setup [3].
- The effective gain can be defined in terms of the expectation values of the annihilation operator $\hat{a}$ for the output and input fields [2]

$$g_{\rm eff} = \frac{|\langle \hat{a}_{\rm out}\rangle|}{|\langle \hat{a}_{\rm in}\rangle|}$$

and for the successfully amplified field this gives

$$g_{\rm eff} = \frac{t_1t_2t_3(2+4|t_1t_2t_3\alpha|^2+|t_1t_2t_3\alpha|^4)}{1+3|t_1t_2t_3\alpha|^2+|t_1t_2t_3\alpha|^4}.$$

- The fidelity F is a measure that quantifies how much the output field differs from an ideally amplified coherent field

$$F(W_1,W_2) = 2\pi\hbar\int W_1(x,p)W_2(x,p)\,dx\,dp.$$

The fidelity obtained for the successfully amplified field with respect to a coherent field $|g_{\rm eff}\alpha\rangle$ is

$$F_{\rm eff} = \frac{(1+2g_{\rm eff}t_1t_2t_3|\alpha|^2+g_{\rm eff}^2t_1^2t_2^2t_3^2|\alpha|^4)e^{-(g_{\rm eff}^2-t_1t_2t_3)^2|\alpha|^2}}{1+3|t_1t_2t_3\alpha|^2+|t_1t_2t_3\alpha|^4}.$$

- Probability of successful amplification is

$$P_{\rm succ} = (1+|t_1t_2t_3\alpha|^2(3+|t_1t_2t_3\alpha|^2))|r_1r_2r_3\alpha|^2e^{|t_1t_2t_3\alpha|^2-|\alpha|^2}.$$

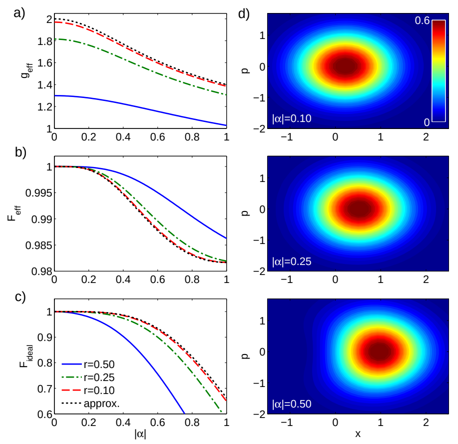
Amplified output field

a) The effective gain of amplification is close to ideal for small $|\alpha|$.

b) Very high values for the effective fidelity obtained for small $|\alpha|$.

c) Fidelity with respect to an ideal output field $|2\alpha\rangle$ is smaller than the effective fidelity.

d) Wigner functions of the output field depend on the input field amplitude.

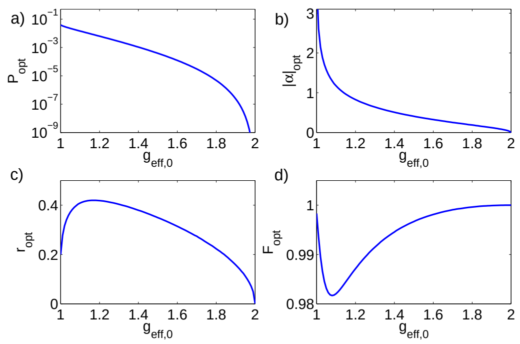


Optimizing the amplification process

- The optimization problem for maximizing the probability of successful amplification with a constraint requiring the effective gain exceeding a threshold value $g_{\rm eff,0}$ can be presented as

$$\max_{g_{\rm eff}\geq g_{\rm eff,0}} P_{\rm succ}(|\alpha|,r_1,r_2,r_3).$$

- As a result we obtain the maximized success probability $P_{\rm opt}$, optimal input field amplitude $|\alpha|_{\rm opt}$, beam splitter reflectivity $r_{\rm opt}$, and the fidelity of the output field $F_{\rm opt}$.



Conclusions

- We have theoretically shown the operational principles of the noiseless amplification in a scheme that adds no external energy to the signal.
- The energy required to amplify the signal originates from stochastic fluctuations in the field itself.
- The proposed amplification scheme is experimentally feasible with existing components [5].

References

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