Quantum state engineering via optimized photon subtraction in traveling optical fields

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Introduction

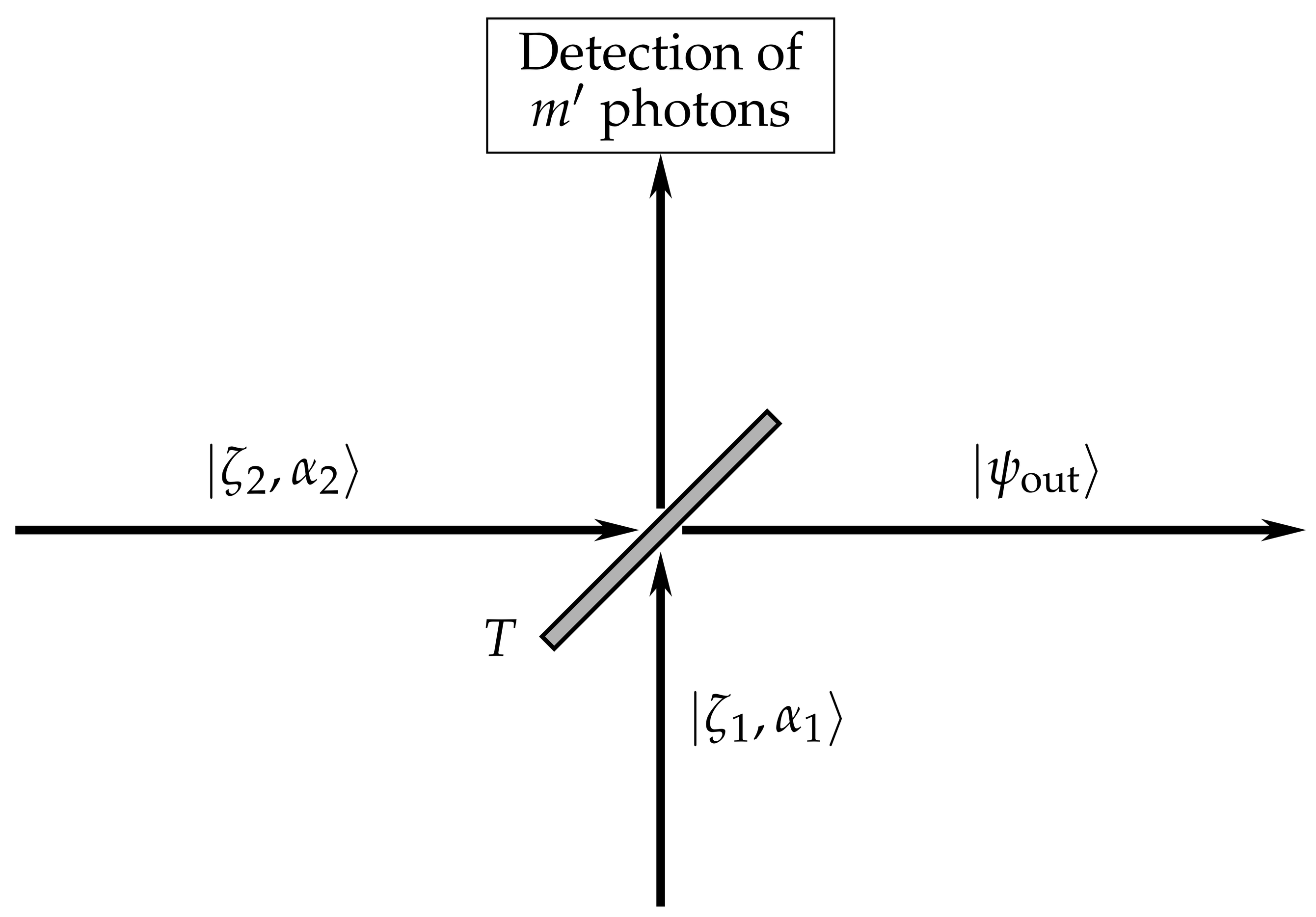
Generation of various nonclassical states of light is still an important topic in quantum optics, owing to the numerous applications of such states in quantum information processing, quantum-enhanced metrology, and fundamental tests of quantum mechanics [1,2]. The preparation of states in traveling optical modes is generally desired in many practical applications. Conditional preparation is a well-established technique for this task. Quantum state engineering has also been extensively studied with the general aim of the preparation of a variety of different nonclassical states in traveling fields in the same single experimental scheme [3–13].

We show that in a single-step photon subtraction scheme consisting of a beam splitter of transmittance T and a photon number resolving detector, it is possible to prepare various nonclassical states containing several photon number states in their number-state expansions. The input states of the scheme are separately prepared squeezed coherent states. The benefit of using such input states is that they can be easily generated experimentally by standard techniques. The desired state emerges at the output after detecting m' photons in the other arm of the setup for a special set of parameters of the input states and a given beam splitter transmittance.

We have determined numerically using a genetic algorithm the parameters to achieve maximal fidelity of the preparation for a large variety of nonclassical states, such as amplitude squeezed states, binomial states, negative binomial states, optical Schrödinger-cat states, and various photon number superpositions. We have shown that the proposed setups can generate these states with high fidelities and success probabilities.

Experimental setup

Scheme for generating nonclassical states:



Photon resolving detection: If the detector in the reflected trigger mode detects m' photons, the state is projected onto $|m'\rangle\langle m'|$, and the transmitted signal mode collapses into the desired conditional photon-subtracted output state $|\psi_{\text{out}}\rangle$.

Output state:

$$|\psi_{\text{out}}\rangle = \mathcal{N}_{\text{out}} \prod_{j=1}^{2} \frac{e^{-\frac{1}{2}|\alpha_j|^2 - \frac{1}{2}\alpha_j^{*2} e^{i\theta_j} \tanh(r_j)}}{\sqrt{\cosh(r_j)}} \sum_{n=0}^{\infty} \frac{\left(\frac{T(1-T)}{2} e^{i\theta_1} \tanh(r_1)\right)^{\frac{n}{2}}}{n!} \times$$

$$\times H_n\left(\beta_1 [e^{i\theta_1}\sinh(2r_1)]^{-\frac{1}{2}}\right) \sum_{m=0}^{\infty} \frac{\left(\frac{T}{2} e^{i\theta_2} \tanh(r_2)\right)^{\frac{m}{2}}}{m!} H_m\left(\beta_2 [e^{i\theta_2}\sinh(2r_2)]^{-\frac{1}{2}}\right) \times$$

$$\times \sum_{k=0}^{n} (-1)^k \binom{n}{k} \binom{m}{k-n+m'} \left(\sqrt{1-T}\right)^{-(2k+m')} \sqrt{m'!(n+m-m')!}\, |n+m-m'\rangle,$$

where $\beta_j = \alpha_j \cosh(r_j) + \alpha_j^* e^{i\theta_j} \sinh(r_j)$. $\quad (j = 1, 2)$

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Numerical results

Genetic algorithm for finding optimal parameters leading to minimal misfit:

$$\varepsilon = 1 - |\langle\psi_{\text{out}}|\Psi_{\text{target}}\rangle|^2,$$

where the quantity $|\langle\psi_{\text{out}}|\Psi_{\text{target}}\rangle|^2$ is the fidelity between the output and the target states.

Probability of generation: $P = \text{Tr}(\hat{\varrho}_3 |m'\rangle\langle m'|)$, where $\hat{\varrho}_3 = \text{Tr}_4(\hat{\varrho}_{34})$.

Approximated nonclassical states:

$$\textit{Binomial state}: \; |p, M\rangle_{\text{B}} = \sum_{n=0}^{M} \left[\binom{M}{n} p^n (1-p)^{M-n}\right]^{\frac{1}{2}} |n\rangle,$$

$$\textit{Negative binomial state}: \; |\eta, M, \varphi\rangle_{\text{NB}} = \sum_{n=0}^{\infty} \left[\binom{M+n-1}{n} \eta^{2n} (1-\eta^2)^M\right]^{\frac{1}{2}} e^{in\varphi} |n\rangle,$$

$$\textit{Resource state}: \; |\psi(\zeta, \chi')\rangle_{\text{RS}} = \hat{S}(\zeta)\left(|0\rangle + \chi' \frac{3}{2\sqrt{2}} |1\rangle + \chi' \frac{\sqrt{3}}{2} |3\rangle\right),$$

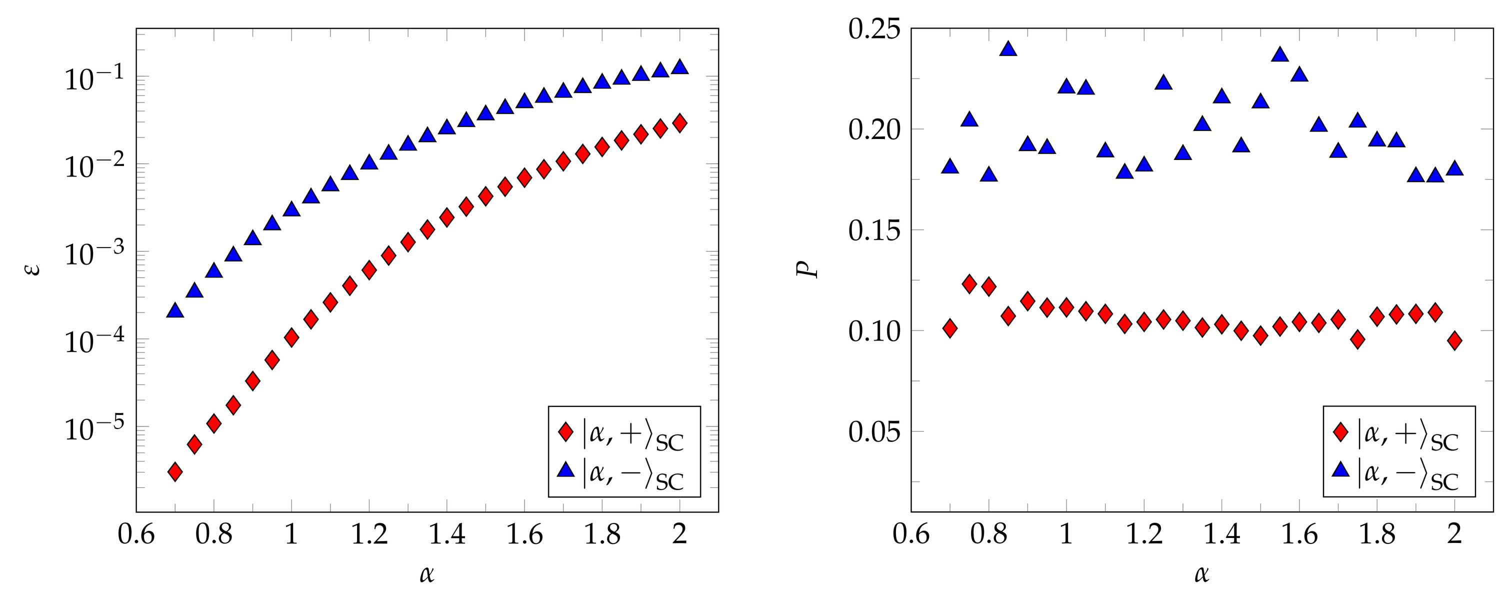
$$\textit{Amplitude squeezed state}: \; |\alpha_0, u, \delta\rangle_{\text{AS}} = c \sum_{n=0}^{\infty} \frac{\sqrt{2\pi}\alpha_0^n}{u\sqrt{n!}} \exp\left[-\frac{(\delta-n)^2}{2u^2}\right] |n\rangle,$$

$$\textit{Schrödinger-cat state}: \; |\alpha, \pm\rangle_{\text{SC}} = \mathcal{N}_{\pm}(|\alpha\rangle \pm |-\alpha\rangle).$$

Results:

state	ε	r_1	θ_1	α_1	ϕ_1	r_2	θ_2	α_2	ϕ_2	T	m'	P
$\|0.6, 10\rangle_{\text{B}}$	2.78×10^{-3}	0.64	1.60	0.04	0.73	0.82	6.10	2.65	0.20	0.75	1	0.246
$\|0.5, 5, \frac{\pi}{4}\rangle_{\text{NB}}$	1.09×10^{-5}	0.14	6.08	0.77	3.39	0.29	4.15	1.38	1.17	0.40	1	0.370
$\|1, 2, 1\rangle_{\text{AS}}$	1.22×10^{-3}	0.23	0.24	0.67	0.59	0.15	6.21	1.27	0.13	0.84	1	0.403
$\|\psi(0.6, 0.03)\rangle_{\text{RS}}$	1.13×10^{-4}	0.06	6.28	0.71	3.09	0.86	6.27	0.49	3.04	0.65	1	0.403
$\|0.8, +\rangle_{\text{SC}}$	1.08×10^{-5}	1.12	3.14	0.00	3.31	0.11	6.28	0.00	4.39	0.75	2	0.122
$\|1.55, +\rangle_{\text{SC}}$	5.47×10^{-3}	1.66	3.14	0.00	0.00	0.24	0.00	0.00	4.85	0.47	2	0.102
$\|0.8, -\rangle_{\text{SC}}$	5.76×10^{-4}	1.51	3.98	0.00	0.38	1.23	1.24	0.01	5.34	0.45	1	0.177
$\|1.55, -\rangle_{\text{SC}}$	4.26×10^{-2}	1.39	3.01	0.00	0.00	0.89	5.67	0.00	1.27	0.22	1	0.236

Generation of Schrödinger-cat states with high fidelity and large probability:



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