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Decoherence and relative phase sensitivity of entangled coherent states

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ABSTRACT

we demonstrate that entanglement and nonclassical properties of entangled coherent states are sensitive to relative phase and more robust against channel decoherence for small values of average photon number. We have analyzed the decoherence due to channel losses and considered two cases: asymmetric and symmetric noise channel. Moreover, we have observed a correlation between entanglement and nonclassical features and found that one of the entangled coherent states is more robust against photon absorption.

1. Introduction

Through peers of history in 1974, Dodonov et al introduced the idea of superposition of coherent states with equally weighted amplitude but having a phase shift of π [1]. In case of superposition, the even-odd superposition coherent state is

$$|\psi\rangle = N\left(|\alpha\rangle + e^{i\phi}|-\alpha\rangle\right), \tag{1}$$

where, $N = [2 + 2\exp(-2|\alpha|^2)\cos\phi]^{\frac{1}{2}}$. On going investigation for better nonclassical states, it has been observed that even-odd superposition coherent states have shown diverse range of nonclassical behavior for particular values of relative phase (ϕ=0, π, $\pi/2$, $|\alpha|^2$) this refers to the relative phase sensitivity of superposition coherent states [2–5]. The reason for this interest is related to their potential applications in quantum information processing [6,7].

Chai focused on the two-mode extension to single-mode even and odd coherent states and studied squeezing as well as statistical properties of even-odd entangled coherent states [8]. Recently, entanglement and nonclassical properties of even-odd entangled coherent states with relative phase equal to the average photon number have been discussed [9]. In addition to that, Ahmad et al introduces the entangled coherent states based on two coherent states shifted in phase by $\pi/2$ and $3\pi/2$ and studied entanglement and nonclassical properties of such states with different values of relative phase [10–12]. Regarding the relationship between entanglement and nonclassical effects, it is proposed that entanglement always corresponds with one of squeezing and antiquating and the larger a nonclassical effect is, the stronger entanglement is [13].

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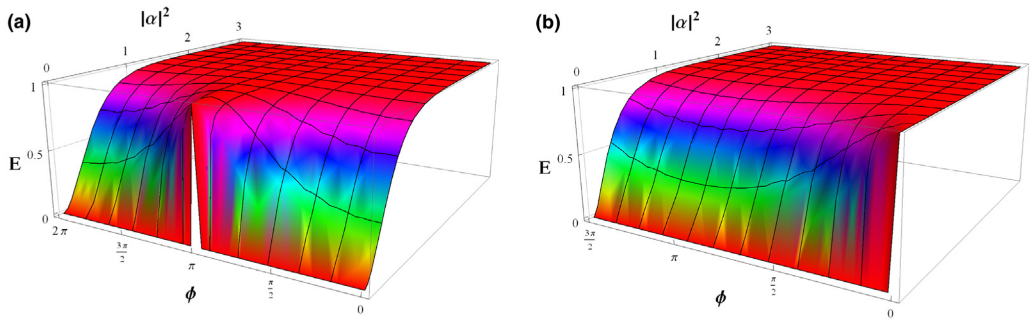

Fig. 1. Entanglement dynamics as a function of relative phase ϕ (a) $|\Phi_3\rangle$, (b) $|\Phi_4\rangle$.

Even-odd entangled coherent states can be written as

$$|\Phi_{1,2}\rangle_{AB} = h_{1,2}e^{i\phi}\left(|\alpha\rangle_A \otimes |-\alpha\rangle_B \pm |-\alpha\rangle_A \otimes |\alpha\rangle_B\right),$$
$$|\Phi_{3,4}\rangle_{AB} = h_{3,4}\left(|\alpha\rangle_A \otimes |\alpha\rangle_B \pm e^{2i\phi}|-\alpha\rangle_A \otimes |-\alpha\rangle_B\right), \quad (2)$$

where $h_{1,2} = [2 \pm 2e^{-4|\alpha|^2}]^{-\frac{1}{2}}$ and $h_{3,4} = [2 \pm 2e^{-4|\alpha|^2}\cos(2\phi)]^{-\frac{1}{2}}$.

As a matter of fact, we have observed that entanglement and nonclassical properties of states $|\Phi_1\rangle$ and $|\Phi_2\rangle$ are not relative phase sensitive and exhibit the same results for all values of relative phase as given in [9]. Hence, we restrict ourself solely to the discussion of states $|\Phi_3\rangle$ and $|\Phi_4\rangle$.

2. Entanglement dynamics

Entangled coherent states have been studied as a resource as well as an input for quantum information protocols [14,15]. Entanglement properties for entangled coherent states have been studied and observed that entanglement dynamics changes abruptly with arbitrary fixed values relative phase [16,9]. In order to calculate entanglement, first we evaluate the reduced density operator because it is useful for the analysis of composite quantum systems. The reduced density operator can be defined as

$$\rho_A^{(i)} = Tr_B|\Phi_i\rangle_{AB}\langle\Phi_i|. \quad (3)$$

The reduced density operator of considered entangled states takes the form:

$$\rho_A^{(3,4)} = h_{3,4}^2\left[|\alpha\rangle\langle\alpha| + |-\alpha\rangle\langle-\alpha| \pm e^{-2(i\phi+|\alpha|^2)}|\alpha\rangle\langle-\alpha| \pm e^{2(i\phi-|\alpha|^2)}|-\alpha\rangle\langle\alpha|\right], \quad (4)$$

The eigenvalues of the reduced density operators for states $|\Phi_3\rangle$ and $|\Phi_4\rangle$ can be defined as

$$\lambda_{A,B}^{(3)} = \frac{1}{2}\left(1 \pm \sqrt{1 - \frac{(1-e^{-4|\alpha|^2})^2}{(1+e^{-4|\alpha|^2}\cos 2\phi)^2}}\right) \quad (5)$$

$$\lambda_{A,B}^{(4)} = \frac{1}{2}\left(1 \pm \sqrt{1 - \frac{(1-e^{-4|\alpha|^2})^2}{(1-e^{-4|\alpha|^2}\cos 2\phi)^2}}\right) \quad (6)$$

The entanglement can be calculated by the following relation

$$E^{(i)} = -\sum_{m=A,B}\lambda_m^{(i)}\log_2\lambda_m^i. \quad (7)$$

Dynamical evolution of entanglement contained in state $|\Phi_3\rangle$ and $|\Phi_4\rangle$ as a function of ϕ is shown in Fig. 1. It can be seen that states $|\Phi_3\rangle$ and $|\Phi_4\rangle$ have maximum entanglement at relative phase π and 0 respectively, regardless of α. Moreover, entanglement also exist in the limit $|\alpha|^2 > 1$ for rest of the relative phase ϕ in both states.

For all values of relative phases on which entanglement is not maximum at $|\alpha|^2 \to 0$ are having an exponential increase in entanglement with the increase in average photon number and become maximal entangled on crossing the limit $|\alpha|^2 > 1$. The factor $e^{2i\phi}$ is responsible for the rapid exponential growth of entanglement in the system under consideration, comprising states $|\Phi_3\rangle$ and $|\Phi_4\rangle$.