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Amplitude-squared squeezing in superposed coherent states

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Abstract. We study amplitude-squared squeezing of the Hermitian operator $Z_\theta = Z_1 \cos\theta + Z_2 \sin\theta$, in the most general superposition state $|\psi\rangle = C_1 |\alpha\rangle + C_2 |\beta\rangle$, of two coherent states $|\alpha\rangle$ and $|\beta\rangle$. Here operators $Z_{1,2}$ are defined by $Z_1 + iZ_2 = [a - \langle\psi| a |\psi\rangle]^2$, a is annihilation operator, θ is angle, and complex numbers $C_{1,2}$, α, β are arbitrary and only restriction on these is the normalization condition of the state $|\psi\rangle$. We define the condition for a state $|\psi\rangle$ to be amplitude-squared squeezed for the operator Z_θ if squeezing parameter $S \equiv [\langle\psi| (\Delta Z_\theta)^2 |\psi\rangle - \langle\psi| N |\psi\rangle + \langle\psi| a |\psi\rangle \langle\psi| a^+ |\psi\rangle] < \frac{1}{2}$, where $N = a^+a$ and $\Delta Z_\theta = Z_\theta - \langle\psi| Z_\theta |\psi\rangle$. We find maximum amplitude-squared squeezing of Z_θ in the superposed coherent state $|\psi\rangle$ with minimum value 0.3268 of the parameter S for an infinite combinations with $\alpha - \beta = 2.16 \exp[\pm i(\pi/4) + i\theta/2]$, $C_2/C_1 = 0.3 \exp[\frac{1}{2}(\alpha\beta^* - \alpha^*\beta)]$ and with arbitrary values of $(\alpha + \beta)$ and θ. For this minimum value of squeezing parameter S, the expectation value of photon number can vary from the minimum value 1.0481 to infinity. Variations of the parameter S with different variables at maximum amplitude-squared squeezing are also discussed.

PACS. 42.50.Dv Nonclassical states of the electromagnetic field, including entangled photon states; quantum state engineering and measurements

1 Introduction

Squeezing [1] is a phenomenon in which variance in one of the quadrature components become less than that in vacuum state or coherent state [2] at the cost of increased fluctuations in the other quadrature component. This is a non-classical phenomenon in the sense that for this effect Glauber-Sudarshan P function [3,4] is less well behaved than a probability density, i.e., it takes on negative values and become more singular than a delta function. Earlier study [5] of squeezing was largely in academic interest only but now its utility in reducing noise in communications [6,7], quantum teleportation [8], dense coding [9], quantum cryptography [10] and in detection of gravitational waves [11] has been well realized.

The definition of squeezing has been generalized to case of several variables [12–15]. Hong et al. [12] introduced the concept of higher-order squeezing by considering the nth order (n is even integer) moments of the quadrature component and defined a state to be nth order squeezed if the expectation value of the nth power of the difference between a field quadrature and its average value is less than what it would be in a coherent state. Another form of higher-order squeezing in terms of real and imaginary parts of square of the amplitude, the so-called 'amplitude-squared squeezing', has been proposed by Hillery [13]. The author considered the operators Y_1 and Y_2, such that $Y_1 + iY_2 = a^2$, with commutation relation $[Y_1, Y_2] = i(2N + 1)$, and defined a state $|\psi\rangle$ to be amplitude-squared squeezed for the operator Y_i ($i = 1$ or 2), if

$$\langle\psi| (\Delta Y_\mathrm{i})^2 |\psi\rangle < \left[\langle\psi| N |\psi\rangle + \frac{1}{2}\right], \tag{1}$$

where $\Delta Y_i = Y_i - \langle\psi| Y_i |\psi\rangle$, $N = a^+a$ and a is annihilation operator. If an optical field generates second harmonic, signal of second-harmonic is proportional to the square of the signal of optical field. Hence amplitude-squared squeezing can be related to the fluctuations of the signal of the second harmonic.

The author pointed out that amplitude-squared squeezing of Y_i depends upon the amplitude of the state, i.e., if a state $|\psi\rangle$ is squeezed for the variable Y_i, this does not mean the displaced state $D(\alpha)|\psi\rangle$ will be also squeezed for Y_i, where $D(\alpha) = \exp(\alpha a^+ - \alpha^* a)$ is the coherent state displacement operator [2]. It should be noted that ordinary squeezing in any state $|\psi\rangle$ is not affected by operation of the displacement operator $D(\alpha)$. To avoid the difficulty of dependence of amplitude-squared squeezing of the variable Y_i on the amplitude of the state, Hillery [13]

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defined the operators Z_1 and Z_2 by

$$Z_1 + iZ_2 = [a - \langle\psi| a |\psi\rangle]^2, \quad (2)$$

which measure the square of the fluctuations of annihilation operator about its mean value. The commutator between operators Z_1 and Z_2,

$$[Z_1, Z_2] = i\left[2N + 1 - 2(a^+ \langle\psi| a |\psi\rangle + \langle\psi| a^+ |\psi\rangle a) + 2\langle\psi| a^+ |\psi\rangle \langle\psi| a |\psi\rangle\right], \quad (3)$$

yields the condition for a state $|\psi\rangle$ to be amplitude-squared squeezed for the variable Z_i ($i = 1$ or 2) as

$$\langle\psi| (\Delta Z_i)^2 |\psi\rangle < \left[\langle\psi| N |\psi\rangle - \langle\psi| a^+ |\psi\rangle \langle\psi| a |\psi\rangle + \frac{1}{2}\right], \quad (4)$$

where $\Delta Z_i = Z_i - \langle\psi| Z_i |\psi\rangle$.

Hillery [14] introduced another type of higher-order squeezing, called sum squeezing and difference squeezing by considering two mode systems and using sum and differences of various bilinear combinations constructed from the creation and annihilation operators. Zhang et al. [15] defined kth-order squeezing based on the operators $A = (a^k + a^{+k})/2$ and $B = (a^k - a^{+k})/2i$ following Hillery [13]. The higher-order squeezing defined [13–15] by different types of definitions is different from Hong and Mandel's higher-order squeezing [12]. However all of squeezed states produced by different kinds of higher-order squeezing definitions are non-classical.

There have been several proposals [16–22] for detection of higher-order squeezing. Recently Shchukin et al. [16] have shown that amplitude-squared squeezing of the variable Y_i can be characterized by homodyne correlation measurements of the moments of annihilation operator, creation operator, quadrature operators and photon number operator. The methods of detection of Hong and Mandel's higher-order squeezing and amplitude-squared squeezing of the variable Y_i using higher-order sub-Poissonian statistics [17] have been recently proposed by Prakash et al. [18,19]. On the similar lines experimental detection of amplitude-squared squeezing of the variable Z_i has also been proposed by Prakash et al. [20]. Method of detection of sum and difference squeezing has been proposed by Hillery [14], Giri et al. [21], and Prakash et al. [22].

Amplitude-squared squeezing can be produced in various processes [23–27] such as nonlinear optical processes, cavities, JC model and Kerr effect. Other possibilities for generating such effect have been proposed by superposition of two or more coherent states. It has been realized that the superposition of two or more coherent state exhibit [28–35] various non-classical effects like squeezing, antibunching, higher-order squeezing and higher-order sub-Poissonian statistics etc. In particular, Yunji et al. [28] studied amplitude-squared squeezing of the operators Y_1 and Y_2 in even coherent state, odd coherent state and the states obtained by their displacement. The authors showed that even and odd coherent states are minimum uncertainty states for the operators Y_1 and Y_2. The authors also reported that the displaced even coherent states can exhibit amplitude-squared squeezing while the displaced odd coherent state can not exhibit amplitude-squared squeezing. There have been several proposals for the generation of optical superposition states in various non-linear processes [36] and in quantum nondemolition measurements [37].

In this paper we study amplitude-squared squeezing of the most general hermitian operator,

$$Z_\theta = Z_1 \cos\theta + Z_2 \sin\theta, \quad (5)$$

in the most general superposed coherent state,

$$|\psi\rangle = C_1 |\alpha\rangle + C_2 |\beta\rangle, \quad (6)$$

of two coherent states $|\alpha\rangle$ and $|\beta\rangle$. Here operators $Z_{1,2}$ are defined by equation (2), and the complex numbers C_1, C_2, α, β and the real θ are all arbitrary and only restriction on these is the normalization condition of the state $|\psi\rangle$, i.e.,

$$|C_1|^2 + |C_2|^2 + 2\mathrm{Re}\left\{C_1^* C_2 \exp\left[-\frac{1}{2}(|\alpha|^2 + |\beta|^2) + \alpha^*\beta\right]\right\} = 1. \quad (7)$$

For simplicity we define squeezing parameter (following Hillery [13]),

$$S = \langle\psi| (\Delta Z_\theta)^2 |\psi\rangle - \langle\psi| N |\psi\rangle + \langle\psi| a |\psi\rangle \langle\psi| a^+ |\psi\rangle, \quad (8)$$

which characterizes amplitude-squared squeezing of Z_θ. If the squeezing parameter $S < \frac{1}{2}$, the state $|\psi\rangle$ is called amplitude-squared squeezed for the operator Z_θ. We use the properties of displacement operator [2] and find conditions on the variables C_1, C_2, α, β and θ for maximum amplitude-squared squeezing in the superposed coherent state $|\psi\rangle$. We show that maximum amplitude-squared squeezing of Z_θ in the superposed coherent state $|\psi\rangle$ with absolute minimum value 0.3268 of the squeezing parameter S occurs for an infinite combinations with $|\alpha - \beta| = 2.16$ and $C_2/C_1 = 0.3\exp[\frac{1}{2}(\alpha\beta^* - \alpha^*\beta)]$ and with arbitrary values $(\alpha + \beta)$ and θ. Variations of the squeezing parameter S with different variables are also discussed.

2 Squeezing parameter S in superposed coherent states $|\psi\rangle$

Single mode coherent state $|\alpha\rangle$ defined by $a|\alpha\rangle = \alpha|\alpha\rangle$ can be written as

$$|\alpha\rangle = \exp\left(-\frac{|\alpha|^2}{2}\right) \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle = D(\alpha)|0\rangle, \quad (9)$$

where $|n\rangle$ is the occupation number and $D(\alpha) = \exp(\alpha a^+ - \alpha^* a)$ is the displacement operator. Using the relation $D^+(\alpha) a D(\alpha) = a + \alpha$, we have

$$\langle\psi'| (\Delta Z_{\theta,|\psi'\rangle})^2 |\psi'\rangle = \langle\psi| (\Delta Z_{\theta,|\psi\rangle})^2 |\psi\rangle, \quad (10)$$

and

$$\langle\psi'|\,N\,|\psi'\rangle - \langle\psi'|\,a^+\,|\psi'\rangle\,\langle\psi'|\,a\,|\psi'\rangle = \langle\psi|\,N\,|\psi\rangle - \langle\psi|\,a^+\,|\psi\rangle\,\langle\psi|\,a\,|\psi\rangle\,, \quad (11)$$

where $|\psi'\rangle = D(\alpha)\,|\psi\rangle$, $\Delta Z_{\theta,|\psi'\rangle} = Z_\theta - \langle\psi'|\,Z_\theta\,|\psi'\rangle$ and $\Delta Z_{\theta,|\psi\rangle} = Z_\theta - \langle\psi|\,Z_\theta\,|\psi\rangle = \Delta Z_\theta$. From equations (8), (10) and (11) we conclude that squeezing parameter S in any state $|\psi\rangle$ is not affected by operation of the displacement operator $D(\alpha)$. This observation and the relation [2], $D(\alpha)\,D(\beta) = \exp[\frac{1}{2}(\alpha\beta^* - \beta\alpha^*)]\,D(\alpha+\beta)$, suggest that we can simplify by writing the superposed coherent state $|\psi\rangle$ (defined in Eq. (6)) as

$$|\psi\rangle = D\left[\frac{1}{2}(\alpha+\beta)\right]\,|\psi_1\rangle\,;\quad |\psi_1\rangle = C_1'\,|\xi\rangle + C_2'\,|-\xi\rangle \quad (12)$$

where $\xi = \frac{1}{2}(\alpha-\beta)$ and $C_{1,2}' = C_{1,2}\exp[\pm\frac{1}{4}(\alpha\beta^*-\beta\alpha^*)] \equiv r_{1,2}\exp(i\phi_{1,2})$. Without loss of generality we label the smaller of r_1 and r_2 as r_2 and the corresponding coherent state as $|-\xi\rangle$ (if $r_1 = r_2$ any one of them is r_2). Therefore we can write the state $|\psi_1\rangle$ in the simpler form,

$$|\psi_1\rangle = K\left[|\xi\rangle + r\,e^{i\phi}\,|-\xi\rangle\right], \quad (13)$$

where $0 \leqslant \phi \equiv (\phi_1 - \phi_2) < 2\pi$, and $0 < r \equiv (r_2/r_1) \leqslant 1$. If we consider $\xi = Ae^{i\theta_\xi}$, we can further write $|\psi_1\rangle$ in the form,

$$|\psi_1\rangle = e^{i\theta_\xi N}\,|\psi_2\rangle\,;\quad |\psi_2\rangle = K\left[|A\rangle + re^{i\phi}\,|-A\rangle\right]. \quad (14)$$

Since we have $Z_\theta = e^{-\frac{1}{2}i\theta N} Z_1\, e^{-\frac{1}{2}i\theta N}$, we get

$$\langle\psi|\,(\Delta Z_\theta)^2\,|\psi\rangle = \langle\psi_2|\,e^{-i\delta N}(\Delta Z_1)^2 e^{i\delta N}\,|\psi_2\rangle = \langle\psi_3|\,(\Delta \mathrm{Z}_1)^2\,|\psi_3\rangle\,, \quad (15)$$

where

$$|\psi_3\rangle = K\left[\left|Ae^{i\,\delta}\right\rangle + re^{i\phi}\left|-Ae^{i\,\delta}\right\rangle\right];\quad \delta = \theta_\xi - \frac{\theta}{2}. \quad (16)$$

We have also

$$\langle\psi|\,N\,|\psi\rangle - \langle\psi|\,a^+\,|\psi\rangle\,\langle\psi|\,a\,|\psi\rangle = \langle\psi_3|\,N\,|\psi_3\rangle - \langle\psi_3|\,a^+\,|\psi_3\rangle\,\langle\psi_3|\,a\,|\psi_3\rangle\,. \quad (17)$$

Therefore we conclude that squeezing parameter S in the state $|\psi\rangle$ will be same as that in the state $|\psi_3\rangle$. Since the state $|\psi_3\rangle$ contains only four parameters (A, r, δ and ϕ) while the state $|\psi\rangle$ contains eight parameters (complex numbers C_1, C_2, α and β) hence it is easier to calculate the squeezing parameter S in the state $|\psi_3\rangle$ than that in the state $|\psi\rangle$ and minimize it for studying maximum amplitude-squared squeezing of Z_θ in the state $|\psi\rangle$. Straightforward calculations lead to

$$\langle\psi_3|\,N\,|\psi_3\rangle - \langle\psi_3|\,a\,|\psi_3\rangle\,\langle\psi_3|\,a^+\,|\psi_3\rangle = 2K^2A^2\left(1 + r^2 - 2r\cos\phi e^{-2A^2}\right) - 2K^4A^2T_2, \quad (18)$$

$$\langle\psi_3|\,Z_1\,|\psi_3\rangle = A^2\cos 2\delta - K^4A^2\left(T_1\cos 2\delta + 4rR\sin\phi\sin 2\delta e^{-2A^2}\right), \quad (19)$$

and

$$\begin{aligned}\langle\psi_3|\,Z_1^2\,|\psi_3\rangle = \frac{1}{2} + \frac{1}{2}\Big[&A^4\cos 4\delta + 2K^4A^4\Big(T_1\cos 4\delta + 4rR\sin\phi\sin 4\delta e^{-2A^2}\Big) - 3K^8A^4\Big(T_1^2\cos 4\delta \\ &- 16r^2R^2e^{-4A^2}\sin^2\phi\cos 4\delta + 8rRT_1\sin\phi\sin 4\delta e^{-2A^2}\Big)\Big] \\ &+ \frac{1}{2}\Big[A^4 + 2K^2A^2\left(1 + r^2 - 2r\cos\phi e^{-2A^2}\right) - 2K^4A^2T_2 - 2K^4A^4T_1 - 3K^8A^4T_2^2 \\ &+ 4K^6A^4T_2\left(1 + r^2 - 2r\cos\phi e^{-2A^2}\right)\Big],\end{aligned} \quad (20)$$

where $R = (1 - r^2)$ and $T_{1,2} = (R^2 \mp 4r^2\sin^2\phi e^{-4A^2})$. We finally get the expression of squeezing parameter,

$$\begin{aligned}S &= \langle\psi_3|(\Delta Z_1)^2\,|\psi_3\rangle - \langle\psi_3|\,N\,|\psi_3\rangle + \langle\psi_3|\,a^+\,|\psi_3\rangle\,\langle\psi_3|\,a\,|\psi_3\rangle \\ &= \frac{1}{2} + \frac{1}{2}\Big[A^4\cos 4\delta + 2K^4A^4\Big(T_1\cos 4\delta + 4rR\sin\phi\sin 4\delta e^{-2A^2}\Big) - 3K^8A^4\Big(T_1^2\cos 4\delta \\ &\quad -16r^2R^2e^{-4A^2}\sin^2\phi\cos 4\delta + 8rRT_1\sin\phi\sin 4\delta e^{-2A^2}\Big)\Big] \\ &\quad + \frac{1}{2}\Big[A^4 - 2K^4A^4T_1 - 3K^8A^4T_2^2 + 4K^6A^4T_2\Big(1 + r^2 - 2r\cos\phi e^{-2A^2}\Big)\Big] - \Big[A^2\cos 2\delta - K^4A^2\Big(T_1\cos 2\delta \\ &\quad + 4rR\sin\phi\sin 2\delta e^{-2A^2}\Big)\Big]^2.\end{aligned} \quad (21)$$

3 Maximum amplitude-squared squeezing in superposed coherent state $|\psi\rangle$ and discussion

For studying the maximum amplitude-squared squeezing of Z_θ, we minimize the parameter S (see Eq. (21)) by varying δ, ϕ, r and A. If we vary the parameter S against δ and ϕ we get the following set of points where the parameter S is minimum,

$$\text{(i)}\quad \phi = 0, \delta = \pm(2n+1)\frac{\pi}{4},\quad \text{(ii)}\quad \phi = \pi, \delta = \pm\frac{n\pi}{2}, \quad (22)$$

for $n = 0, 1, 2, 3, 4, 5, \ldots$ Therefore we get the final expressions of the parameter S that are minimum against the variations in δ and ϕ as,

$$S_{min\ \text{for}\ \phi,\delta} = \frac{1}{2} - \frac{8rR^2A^4e^{-2A^2}}{[1 + r^2 + 2re^{-2A^2}]^3}, \quad (23)$$

and

$$S_{min\ \text{for}\ \phi,\delta} = \frac{1}{2} + \frac{8A^4R^2r}{\left[1 + r^2 - 2re^{-2A^2}\right]^4}\left[2r - (1 + r^2)e^{-2A^2}\right], \quad (24)$$

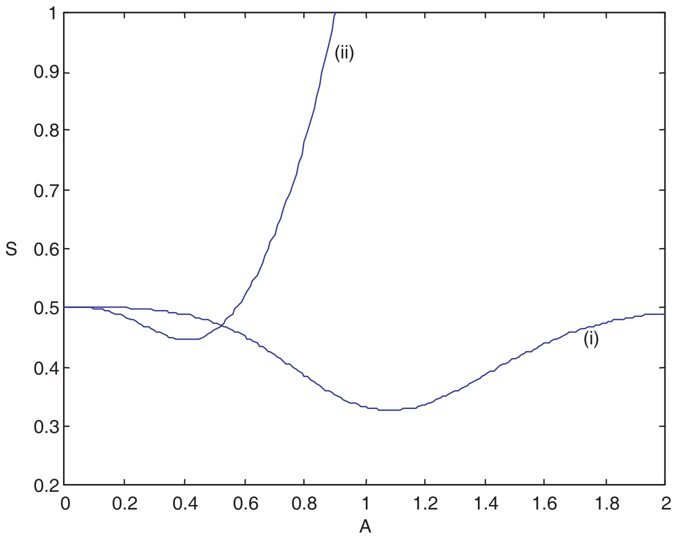

Fig. 1. (i) Variation of the parameter S with A at $\delta = \frac{\pi}{4}$, $\phi = 0$ and $r = 0.3$. (ii). Variation of the parameter S with A at $\delta = 0$, $\phi = \pi$ and $r = 0.28$.

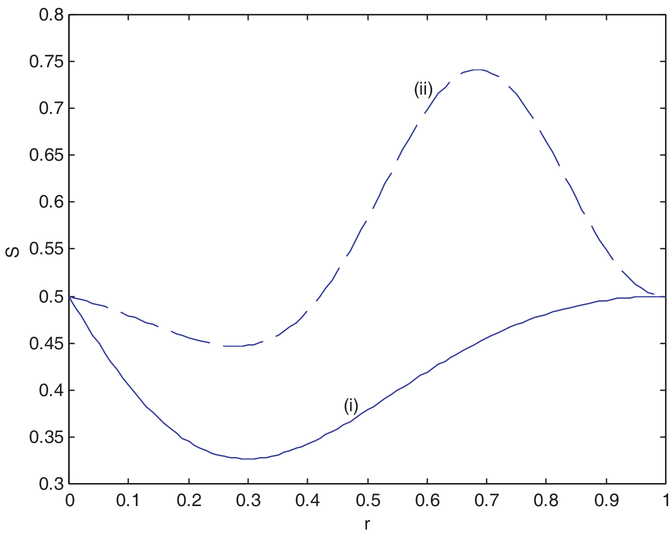

Fig. 3. (i) Variation of the parameter S with r at $\delta = \frac{\pi}{4}$, $\phi = 0$ and $A = 1.08$. (ii) Variation of the parameter S with r at $\delta = 0$, $\phi = \pi$ and $A = 0.41$.

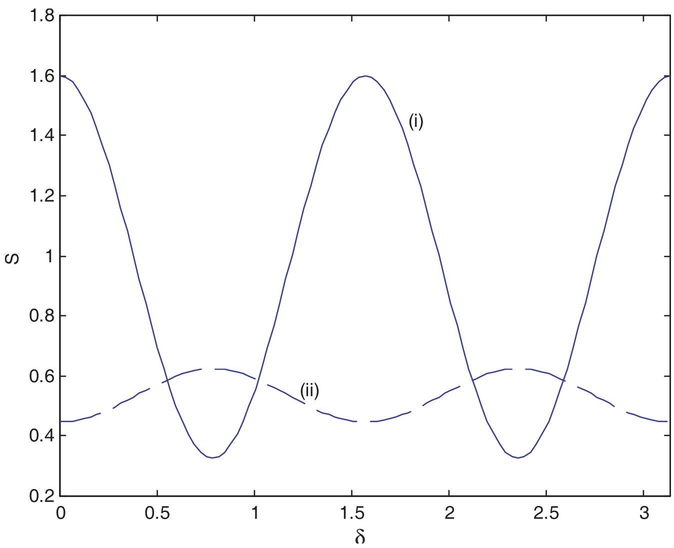

Fig. 2. (i) Variation of the parameter S with δ at $\phi = 0$, $r = 0.3$ and $A = 1.08$. (ii) Variation of the parameter S with δ at $\phi = \pi$, $r = 0.28$ and $A = 0.41$.

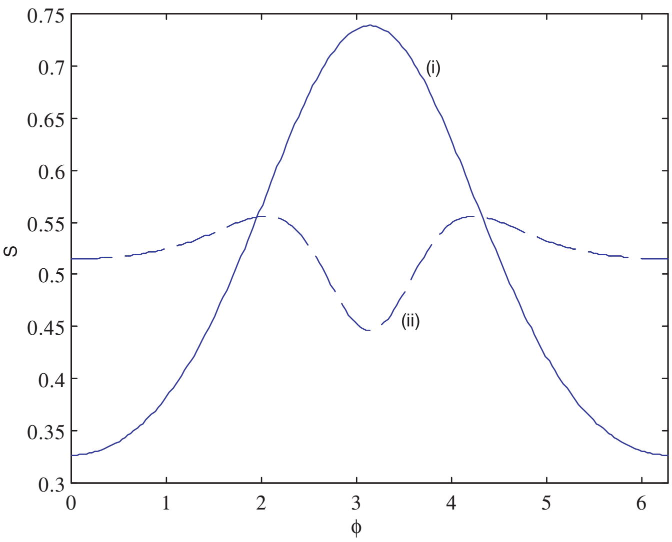

Fig. 4. (i) Variation of the parameter S with ϕ at $\delta = \frac{\pi}{4}$, $r = 0.3$ and $A = 1.08$. (ii) Variation of the parameter S with ϕ at $\delta = 0$, $r = 0.28$ and $A = 0.41$.

for the conditions (i) and (ii) respectively. We calculate the minimum value of the parameter S for both conditions by computer programming. We get the minimum value 0.3268 of the parameter S (for the condition (i)) at $A = 1.08$ and $r = 0.3$, and the minimum value 0.4465 of the parameter S (for the condition (ii)) at $A = 0.41$ and $r = 0.28$. Variations of the squeezing parameter S with x, r, δ and ϕ for both conditions are shown in Figures 1–4.

Since the squeezing parameter S in any state does not change on operation of displacement operator we conclude that the same maximum amplitude-squared squeezing of Z_θ in the state $|\psi\rangle$ occurs with the absolute minimum value 0.3268 of the parameter S. Therefore we finally conclude, in terms of the variables (Z_1, Z_2, α, β and θ) considered originally, that the maximum amplitude-squared squeezing of Z_θ in the state $|\psi\rangle$ occurs for an infinite combinations with, $\alpha - \beta = 2.16\exp[i(\pm\frac{\pi}{4} + \frac{\theta}{2})]$, $C_2/C_1 = 0.3\exp[\frac{1}{2}(\alpha\beta{*} - \alpha{*}\beta)]$ and with arbitrary values of $(\alpha+\beta)$ and θ. Since the action of the displacement operator does not affect the squeezing parameter S but can change photon number hence this large amplitude-squared squeezing can be produced at large intensities also. The minimum value of average photon number that can produce such large amplitude-squared squeezing in the state $|\psi\rangle$ with minimum value 0.3268 of the parameter S, is 1.0481 which occurs at $(\alpha + \beta) = 0$. For this minimum value of squeezing parameter, therefore the expectation value of photon number can vary from the minimum value 1.0481 to infinity because there is no upper limit to it as $(\alpha + \beta)$ is arbitrary.

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