ISSN 2320-5407 International Journal of Advanced Research (2015), Volume 3, Issue 8, 467-478

ISSN NO. 2320-5407

Journal homepage: http://www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH

RESEARCH ARTICLE

Non-classical Properties of New Even And Odd Deformed Photon Added Nonlinear Coherent States

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Manuscript Info

Manuscript History:

Received: 26 June 2015
Final Accepted: 20 July 2015
Published Online: August 2015

Key words:

Nonlinear Coherent States , Dual Coherent states , Sub-Poissonian Statistics, Non-Classical Properties

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Abstract

In this paper a new kind of even and odd deformed photon added nonlinear coherent states (CSs) will be introduced. Nonlinearity feature will be considered through a special potential function known as Poschl- Teller (P-T) potential in which in the case $f(n)=1$ they lead to linear states. In addition for proving that these states are CSs positive definite measure has been specified. Finally statistical properties such as Mandel's Q parameter, second order correlation function and squeezing have been considered. Also beside the standard CSs, dual pair of the introduced states have been calculated due to the lack of the non-classical properties and this was the only motivation for going towards dual CSs .

INTRODUCTION

CSs are significant in many branches of physics [1,2]. CSs, $|\alpha\rangle$, defined as the eigenstates of the harmonic oscillator annihilation operator, $\hat{a}|\alpha\rangle = a|\alpha\rangle$, [3] that have properties like classical radiation field. In addition there are states of the electromagnetic field in which their features such as squeezing, higher order squeezing, anti bunching and Sub- Poissonian statistics [4,5] are strictly quantum mechanical in nature. Such states are called non-classical states. CSs define the limit between the classical and non-classical behavior of the radiation field. Non-classical states play an important role in understanding the fundamentals of quantum physics and also have many applications in quantum information processing [6] . Recently there has been an interest focused on the studying of different Non-classical states, since many schemes have been proposed for their generation. The most common and newly developed example for the suggested scenario is Photon Added Coherent States (PACSs) which was first introduced by Agarwal and Tara [7]. They are the result of successive elementary one- photon excitations of a CS and also is an intermediate state between the Fock state and the CS. It is also worth mentioning that PACSs are a good candidate for the representation of the Sub-Poissonian behavior. It has been shown in [7] that PACSs can be produced in the process of the atom-field interaction in a cavity. Since then the photon added squeezed states [8-10] , the photon thermal states [11-12] , and the photon added even and odd CSs [13-14], etc, have been introduced. Most of the theoretical studies concerning these states have concentrated on their generation and the feasible occurrence of different non-classical effects exhibited by them. More recently an effective way of generating PACSs in a traveling light beam by means of the conditional measurements on a beam splitter was also proposed [15-16]. On the other hand the experimental schemes for the generation of the PACSs may be found in the literature. Among them, we may refer to [17] and specially to the recent work of Zawatta et al that they have been able to experimentally generate single PACSs and complete characterization by quantum tomography [18]. This paper is organized as follows: In section 2 new nonlinear CSs will be defined. In the next section which is one of main purposes of this paper even photon added nonlinear (EPAN) CSs and odd photon added nonlinear (OPAN) CSs will be introduced and in the rest of this section resolution of the identity property will be calculated for the introduced states. Section 5 is devoted to studying of physical and statistical properties such as Mandel's Q parameter, second order correlation and squeezing effects. Final remarks and conclusions are included in the last section.

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2- Definition of new nonlinear coherent states (NCSs)

The NCSs method is based on the deformation of standard annihilation and creation operator in which they are defined with an intensity dependent function f(n). It should be noted that the generalized annihilation (creation) operator associated with NCSs is given by,

$$A = af(n), \qquad A^{\dagger} = f^{\dagger}(n)a^{\dagger} \tag{1}$$

where $a^{\dagger}$ and a are creation and annihilation operators of the standard harmonic oscillator, respectively, and f(n) is a reasonably well-behaved and non-negative function ,i.e, $f^{\dagger}(n) = f(n)$ which is called nonlinearity function. The commutation relation between A and $A^{\dagger}$ reads as ,

$$\left[A, A^{\dagger}\right] = (n+1)f^{\dagger}(n+1)f(n+1) - nf^{\dagger}(n)f(n) \tag{2}$$

Obviously the inherent property of the nonlinear algebra depends on the choice of nonlinearity function f(n). Apparently for f(n)=1 we regain the Heisenburg algebra. NCSs, $\left|\alpha, f\right\rangle$, are defined as right eigenstates of the generalized annihilation operator A as follows

$$A\left|\alpha, f\right\rangle = \alpha\left|\alpha, f\right\rangle \tag{3}$$

The Fock space representation of these states is explicitly expressed as

$$\left|\alpha, f\right\rangle = C_f \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}\left[f(n)\right]!}\left|n\right\rangle \tag{4}$$

Where C_f is the normalization constant , α is a complex number and $\left[f(n)\right]! = f(n)f(n-1)...f(1)f(0)$ and by convention $\left[f(0)\right]! = 1$. Now we will proceed to determine an operator $B^{\dagger}$ which is conjugate of the operator A . In fact the canonical conjugate of the generalized annihilation and creation operators A and $A^{\dagger}$ are given by,

$$B = a\frac{1}{f(n)}, \qquad B^{\dagger} = \frac{1}{f(n)}a^{\dagger} \tag{5}$$

So it can be said that A and $B^{\dagger}$ and their conjugates satisfy the following algebras,

$$\left[A, B^{\dagger}\right] = 1, \qquad \left[B, A^{\dagger}\right] = 1 \tag{6}$$

The displacement- type operators are defined as $D(\beta) = e^{\beta B^{\dagger} - \beta^* A}$ and $\tilde{D}(\beta) = e^{\beta A^{\dagger} - \beta^* B}$ in which by applying them on the vacuum state of the radiation field the results will be the state in (4), such that,

$$\left|\beta, f\right\rangle = D(\beta)\left|0\right\rangle = C_f \sum_{n=0}^{\infty} \frac{\beta^n \left[f(n)\right]!}{\sqrt{n!}}\left|n\right\rangle \tag{7}$$

3- Introducing an explicit form for the EPANCSs and OPANCSs

According to the introduced method of Agarwal and Tara four classes will be written for the defined states. Two classes are related to the EPANCSs and OPANCSs and the others would be their dual form. Now by repeatedly operating photon creation operator for m times on the NCSs and also dual NCSs we obtain the following classes,

$$\left|\alpha,m,f\right\rangle_e=(C_e)^{-1/2}\sum_{n=0}^{\infty}\frac{\alpha^{2n}\sqrt{(2n+m)!}}{(2n)![f(2n)]!}\left|2n+m\right\rangle \tag{8-a}$$

$$\left|\beta,m,f\right\rangle_e=(C_e)^{-1/2}\sum_{n=0}^{\infty}\frac{\beta^{2n}[f(2n)]!\sqrt{(2n+m)!}}{(2n)!}\left|2n+m\right\rangle \tag{8-b}$$

$$\left|\alpha,m,f\right\rangle_o=(C_o)^{-1/2}\sum_{n=0}^{\infty}\frac{\alpha^{2n+1}\sqrt{(2n+m+1)!}}{(2n+1)![f(2n+1)]!}\left|2n+m+1\right\rangle \tag{8-c}$$

$$\left|\beta,m,f\right\rangle_o=(C_o)^{-1/2}\sum_{n=0}^{\infty}\frac{\beta^{2n+1}[f(2n+1)]!\sqrt{(2n+m+1)!}}{(2n+1)!}\left|2n+m+1\right\rangle \tag{8-d}$$

where α and β are arbitrary complex variables with the polar forms $\alpha=re^{i\phi}$ and $\beta=re^{i\phi}$ with $0\le r\le\infty$ and $0\le\phi\le 2\pi$. The normalization constants of each of the above states can be determined easily as,

$$|C_e|=\sum_{n=0}^{\infty}\frac{(|\alpha|)^{4n}(2n+m)!}{((2n)!)^2([f(2n)]!)^2} \tag{9-a}$$

$$|C_e|=\sum_{n=0}^{\infty}\frac{(|\beta|)^{4n}(2n+m)!([f(2n)]!)^2}{((2n)!)^2} \tag{9-b}$$

$$|C_o|=\sum_{n=0}^{\infty}\frac{(|\alpha|)^{4n+2}(2n+m+1)!}{((2n+1)!)^2([f(2n+1)]!)^2} \tag{9-c}$$

$$|C_o|=\sum_{n=0}^{\infty}\frac{(|\beta|)^{4n+2}(2n+m+1)!([f(2n+1)]!)^2}{((2n+1)!)^2} \tag{9-d}$$

4- Resolution of the identity property for EPANCSs and OPANCSs

If a quantum state is to be known as a CS, it should satisfy the resolution of the identity condition. In this section this property for the defined states in (8) will be considered. Resolution of the identity property for these states take the following forms,

$$\int_{\mathbb{C}} d^2\alpha K_e\left(|\alpha|^2\right)\left|\alpha,m,f\right\rangle_{e\,e}\left\langle\alpha,m,f\right|=\sum_{n=0}^{\infty}\left|2n\right\rangle\left\langle 2n\right|=I_e \tag{10-a}$$

$$\int_{\mathbb{C}} d^2\alpha K_o\left(|\alpha|^2\right)\left|\alpha,m,f\right\rangle_{o\,o}\left\langle\alpha,m,f\right|=\sum_{n=0}^{\infty}\left|2n+1\right\rangle\left\langle 2n+1\right|=I_o \tag{10-b}$$

$$\int_{\mathbb{C}} d^2\beta K_e\left(|\beta|^2\right)\left|\beta,m,f\right\rangle_{e\,e}\left\langle\beta,m,f\right|=\sum_{n=0}^{\infty}\left|2n\right\rangle\left\langle 2n\right|=I_e \tag{10-c}$$

$$\int_{\mathbb{C}} d^2\beta K_o\left(|\beta|^2\right)\left|\beta,m,f\right\rangle_{o\,o}\left\langle\beta,m,f\right|=\sum_{n=0}^{\infty}\left|2n+1\right\rangle\left\langle 2n+1\right|=I_o \tag{10-d}$$

Where K and K determine definite positive measures for EPANCSs and OPANCSs. The specified weight functions satisfy following equations,

$$2\pi\,\Gamma(\nu)\int_0^\infty r^{2n+1} N_e^{-1} K_e\left(|\alpha|^2\right) = \frac{\Gamma^2(2n+1)\,\Gamma(2n+\nu+1)}{\Gamma(2n+m+1)} \tag{11-a}$$

$$2\pi\,\Gamma(\nu)\int_0^\infty r^{2n+2} N_e^{-1} K_e\left(|\beta|^2\right) = \frac{\Gamma^2(2n+1)}{\Gamma(2n+m+1)\Gamma(2n+\nu+1)} \tag{11-b}$$

$$2\pi\,\Gamma(\nu)\int_0^\infty r^{2n+1} N_o^{-1} K_o\left(|\alpha|^2\right) = \frac{\Gamma^2(2n+2)\,\Gamma(2n+\nu+2)}{\Gamma(2n+m+2)} \tag{11-c}$$

$$2\pi\,\Gamma(\nu)\int_0^\infty r^{2n+2} N_o^{-1} K_o\left(|\beta|^2\right) = \frac{\Gamma^2(2n+2)}{\Gamma(2n+m+2)\Gamma(2n+\nu+2)} \tag{11-d}$$

with the help of the definition of the meijer's G-function, it follows that

$$\int_{\phi=0}^\infty dx\; x^{k-1} G_{p,q}^{m,n}\left(\begin{vmatrix} a_1,\dots,a_n,a_{n+1},\dots,a_p \\ b_1,\dots,b_n,b_{n+1},\dots,b_q \end{vmatrix}\right) = \frac{1}{\beta^k}\,\frac{\prod_{j=0}^{m}\Gamma\left(b_j+k\right)\prod_{j=0}^{n}\Gamma\left(1-a_j-k\right)}{\prod_{j=m+1}^{m}\Gamma\left(1-b_j-k\right)\prod_{j=n+1}^{p}\Gamma(a_j+k)} \tag{12}$$

Where β, $a_j\ (j=1,\dots,p)$ and $b_h\ (h=1,\dots,q)$ are complex numbers. In addition numbers m, n, p, q are integers with $0 \le n \le p$, $0 \le m \le q$. By substituting the relevant equations and using Eqs (8), we have,

$$K_e\left(|\alpha|^2\right) = \frac{|C_e|}{2\pi\,\Gamma(\nu)} G\left([[\ ],[0,m-1],[-1,-1,\nu-1,0],[\ ]],r\right) \tag{13-a}$$

$$K_e\left(|\beta|^2\right) = \frac{|C_e|}{2\pi\,\Gamma(\nu)} G\left([[\ ],[0,0,m-1,\nu-1],[-1,-1,0,0],[\ ]],r\right) \tag{13-b}$$

$$K_o\left(|\alpha|^2\right) = \frac{|C_o|}{2\pi\,\Gamma(\nu)} G\left([[\ ],[0,m-1],[-1,-1,\nu-1,0],[\ ]],r\right) \tag{13-c}$$

$$K_o\left(|\beta|^2\right) = \frac{|C_o|}{2\pi\,\Gamma(\nu)} G\left([[\ ],[0,0,m-1,\nu-1],[-1,-1,0,0],[\ ]],r\right) \tag{13-d}$$

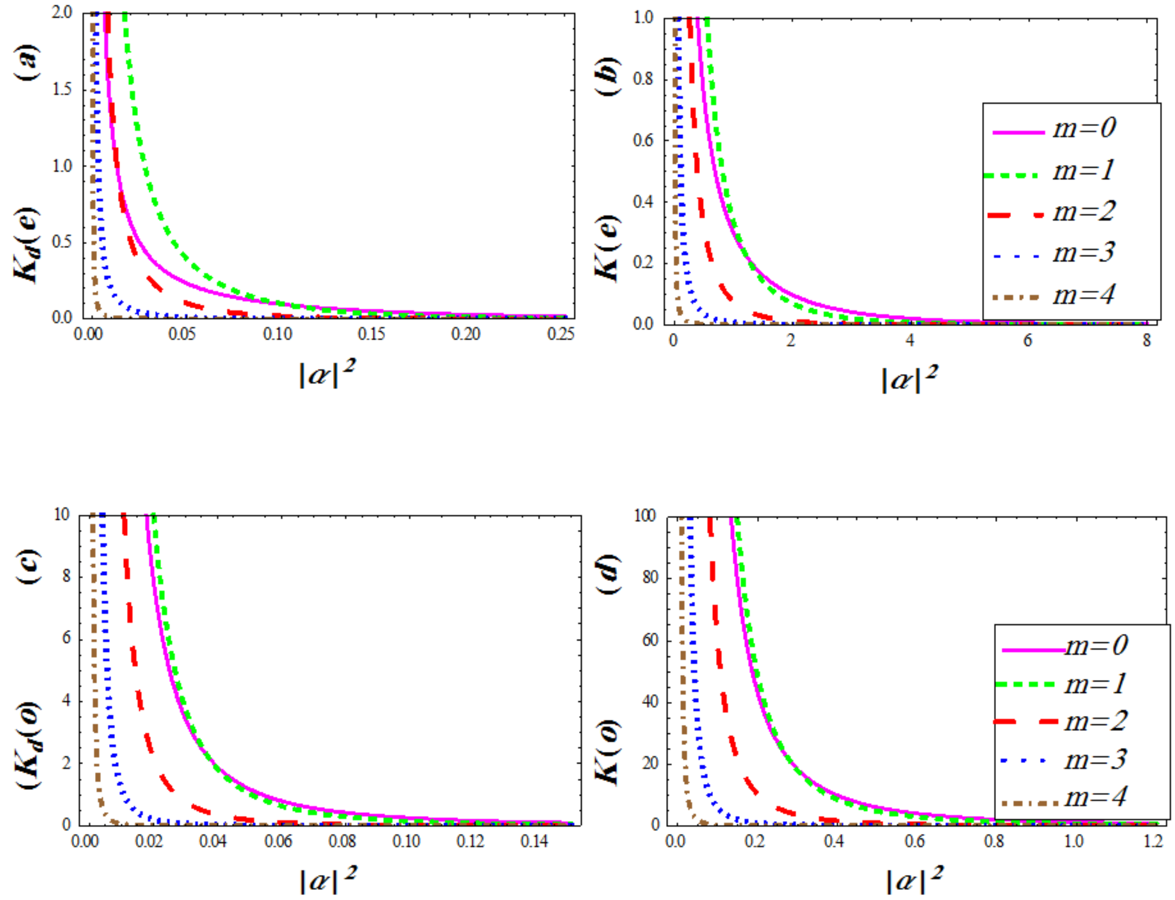


Figure 1 : Plots of the measure for different values of m and fixed $\nu = 3$ for the OPANCSs and EPANCSs in both of the classes associated with the P-T potential.

Positivity of the measures have been shown for different values of m and fixed $\nu = 3$ in all of the classes. As it is seen the positivity of the diagrams show that introduced states are CSs. (Hint: index d in all of the plots and calculations implies dual class in both even and odd classes).

5- Physical and statistical properties of the EPANCSs and OPANCSs

In this section a well-known physical system ,i.e, P-T potential will be defined. This system plays an important role in atomic and molecular physics (See [19] and references therein) . The introduced system has a non degenerate spectrum: $e_n = n(n+\nu), \quad \nu\rangle 0$. In the case $\nu = 2$, it will be the identifier of one dimensional potential well. According to the proposed formalism in [20-21] the non-linearity function is easily obtained as follows,

$$f\,(n) = \sqrt{n+\nu} \tag{14}$$

5-1 Considering statistical properties of the EPANCSs and OPANCSs

Studying non-classical features of a quantum state is a very well known method for checking non-classicality. For this purpose statistical properties such as Mandel's Q parameter, second order correlation function and squeezing effects will be evaluated.

- Mandel's Q parameter

The photon statistics of a quantum state can be conveniently be studied by Mandel's Q parameter, defined as follows,

$$Q = \frac{\langle N^2 \rangle - \langle N \rangle^2 - \langle N \rangle}{\langle N \rangle} \tag{15}$$

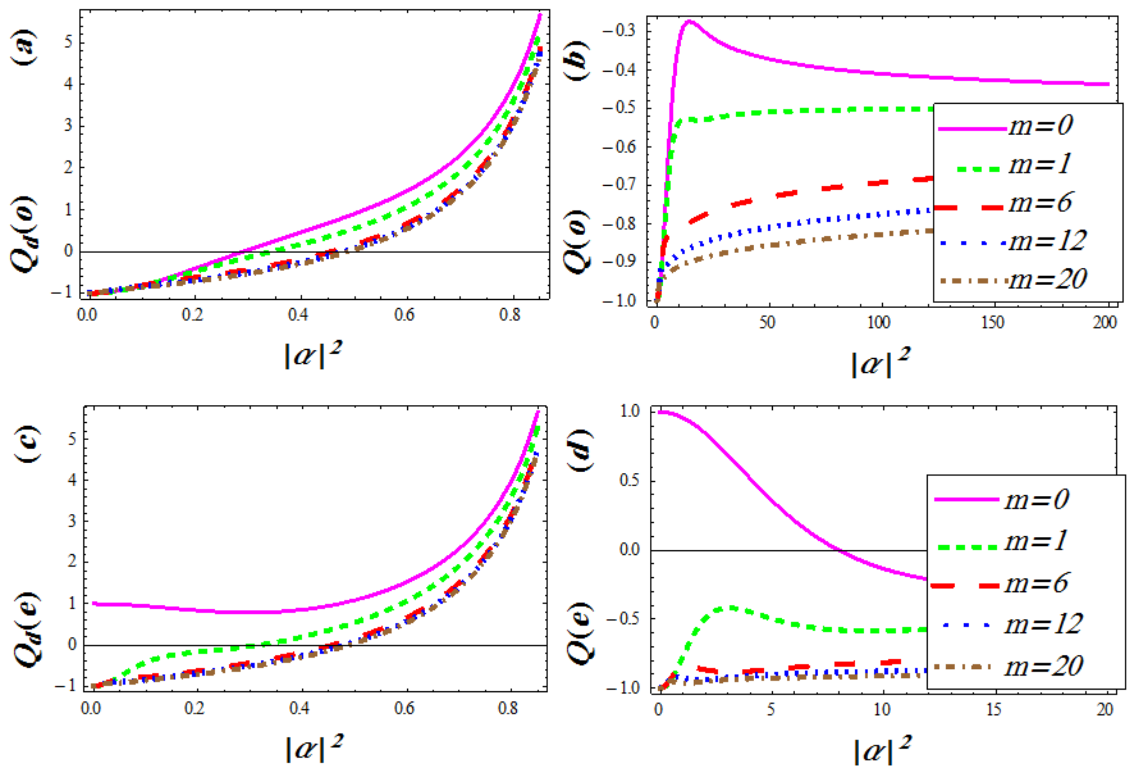


Figure 2: Plots of Mandel's parameter versus $|\alpha|^2$ for different values of m and fixed $\nu = 3$ for the OPANCSs and EPANCSs in both of the classes associated with P-T potential.

A negative Q indicates that the photon number distribution is Sub-Pissonian and it has a non-classical property. A positive Q shows Super-Poissonian distribution and finally Q=0 indicates Poissonian statistics. In the plotted diagrams in (a) and (b), as it is seen Mandel's parameters have been plotted for different values of m and fixed $\nu = 3$ in the class OPANCSs. Based on the diagrams both of them obey from Sub-Poissonian statistics which is a remarkable characteristic of non-classical properties. In the even class the same behavior is visible but the case m=0 in the dual EPANCSs represents Super-Poissonian statistics in which it can be a good candidate for classical behavior.

- Second order correlation function

In the rest of the statistical properties anti bunching effect of the EPANCSs and OPANCSs given by Eqs (8) will be studied. It is worth mentioning that although there are quantum states in which Super/Sub Poissonian statistical behavior is appeared with bunching and anti bunching effect, this is not completely true. The best proposal is proceeding with the second order correlation function defined as,

$$g^{2}(0)=\frac{\left\langle a^{2}a^{\dagger^{2}}\right\rangle}{\left\langle a^{\dagger}a\right\rangle^{2}} \tag{16}$$

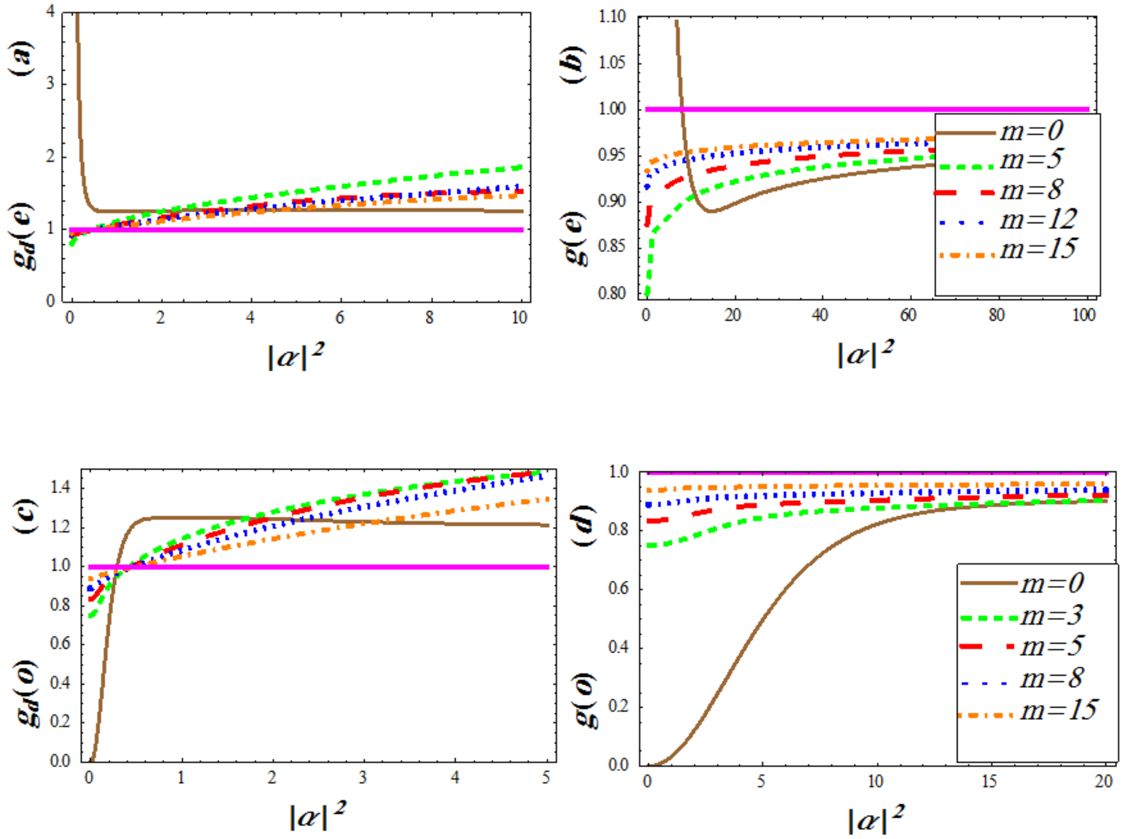


Figure 3: Diagrams of the second order correlation function via $|\alpha|^2$ for different values of m and fixed $\nu=3$ for the OPANCSs and EPANCSs in both of the classes associated with the P-T potential**.**

If the second order correlation function of a light field is less than 1, i.e, $g^{2}\langle 1$, it can be said that field shows anti bunching effect while $g^{2}\rangle 1$ is identifier of the bunching effect and $g^{2}=0$ corresponds to the standard photon added CSs. According to the plotted diagrams for various values of m and fixed $\nu=3$, second order correlation function for even and odd PACSs has anti bunching behavior while dual form in the even class exhibits bunching effect. In addition odd PACSs in the dual form possess anti bunching characteristic.

- Squeezing properties of the EPANCSs and OPANCSs

Squeezing is a very famous non-classical effect which is a phenomenon that variance in one of the quadrature becomes less than that in the vacuum state or CS. In the other words for checking the quantum fluctuations of the quadrature of the field, we consider the Hamiltonian operators $X=\frac{a+a^{\dagger}}{\sqrt{2}}$ and $P=\frac{a-a^{\dagger}}{\sqrt{2}i}$ with commutation relation $[X,P]=i$. Definitions of the variances of the position and momentum are given by

$S_x = 2\langle(\Delta X)^2\rangle - 1$ and $S_p = 2\langle(\Delta P)^2\rangle - 1$, for quadrature squeezing in X and P respectively. The squeezing parameters are written as

$$S_x = 2\langle a^\dagger a\rangle + \langle a^2 + a^{\dagger 2}\rangle - \langle a\rangle^2 - \langle a^\dagger\rangle^2 - 2\langle a\rangle\langle a^\dagger\rangle \tag{17-a}$$

$$S_p = 2\langle a^\dagger a\rangle - \langle a^2 + a^{\dagger 2}\rangle + \langle a\rangle^2 + \langle a^\dagger\rangle^2 - 2\langle a\rangle\langle a^\dagger\rangle \tag{17-b}$$

It is said for a state squeezed in X or P components if satisfies the inequalities $-1 \le S_x \prec 0$ and $-1 \le S_p \prec 0$, respectively. The above expectation values corresponding to EPANCSs and OPANCSs associated with the P-T potential have been calculated in the appendix.

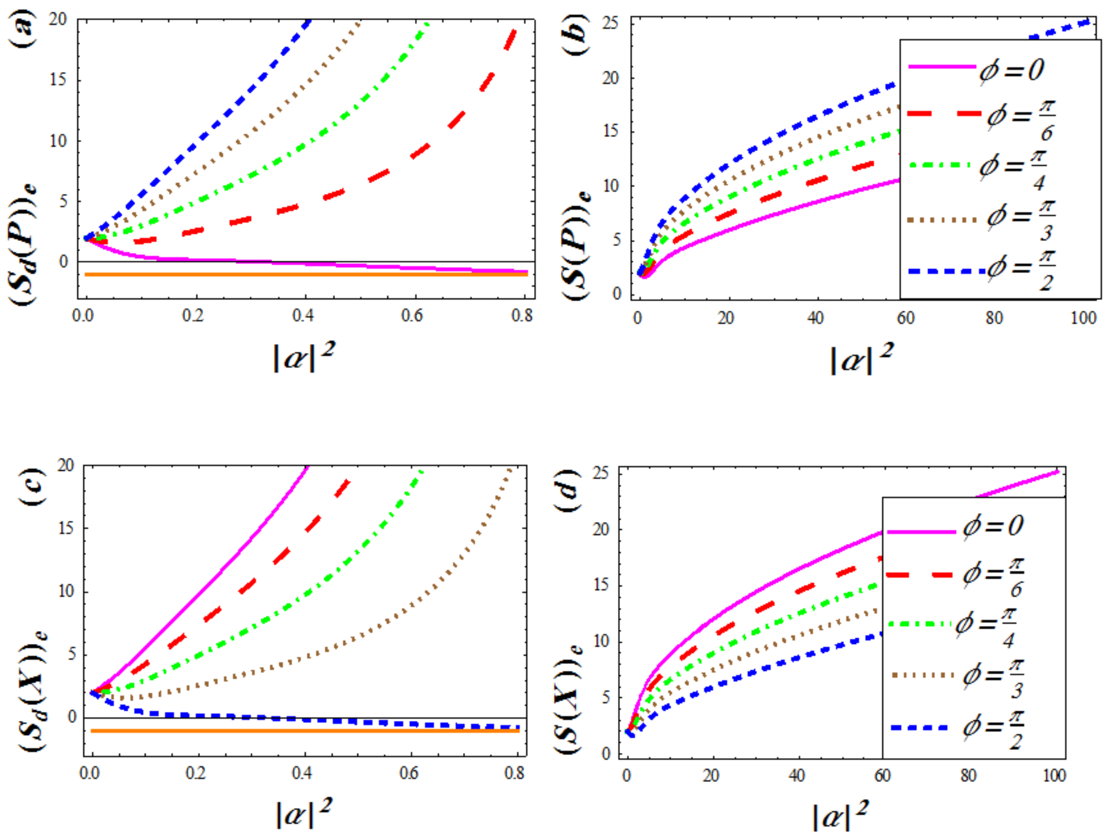


Figure 4: Diagrams of the squeezing in the even classes for both of the quadrature versus $|\alpha|^2$ for different values of ϕ and fixed $\nu = 3$ for the OPANCSs and EPANCSs in both of the classes associated with P-T potential.

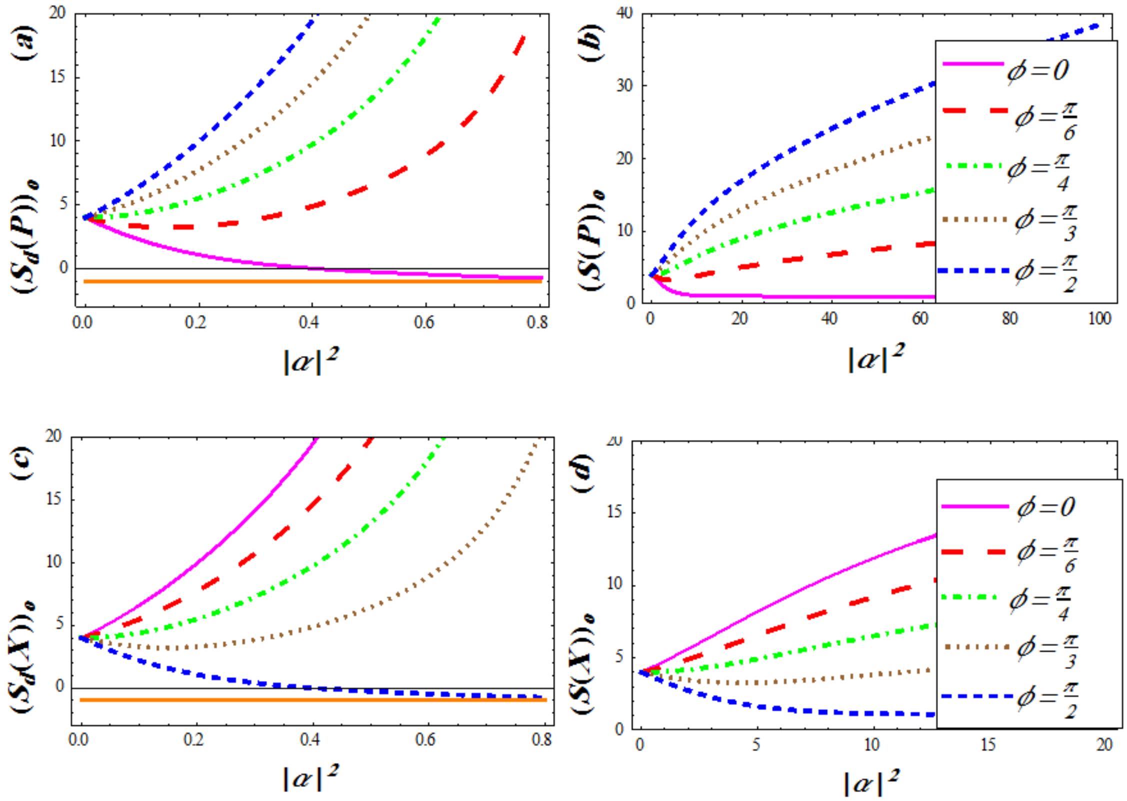


Figure 5: Diagrams of the squeezing in the odd classes for both of the quadrature versus $|\alpha|^2$ for different values of ϕ and fixed $\nu = 3$ for the OPANCSs and EPANCSs associated with P-T potential.

As it is clear in the even and odd classes, the standard CSs have no squeezing for different values of ϕ and this was the motivation for writer to go forward dual form of the them in which for both of the components, i.e, S(P) and S(X) for $\phi = 0$ and $\phi = \frac{\pi}{2}$, respectively squeezing exists .

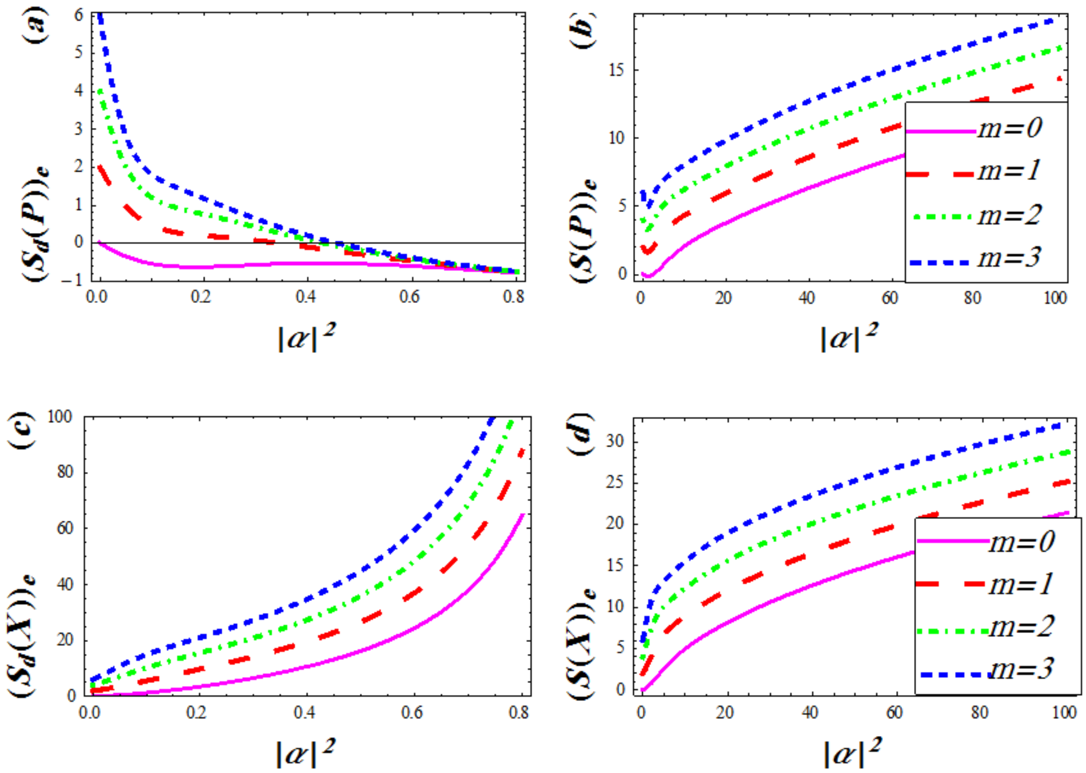
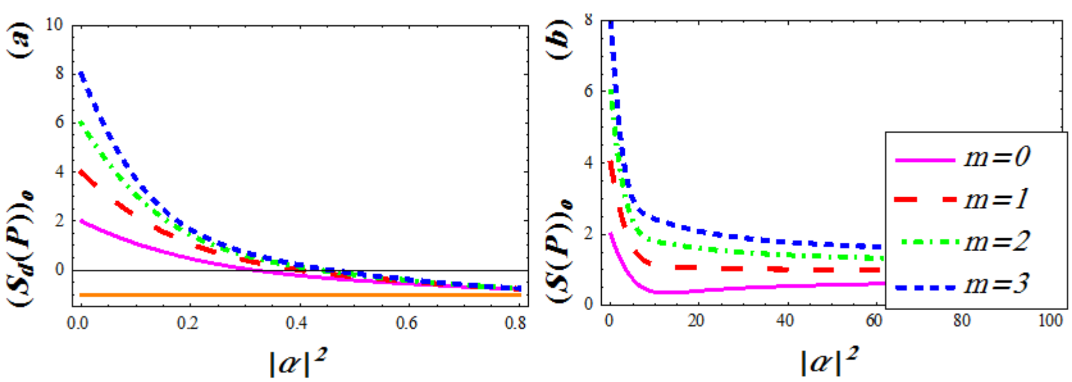


Figure 6: Diagrams of the squeezing versus $|\alpha|^2$ for different values of m and fixed $\nu = 3$ for the EPANCSs in both of the classes associated with P-T potential**.**



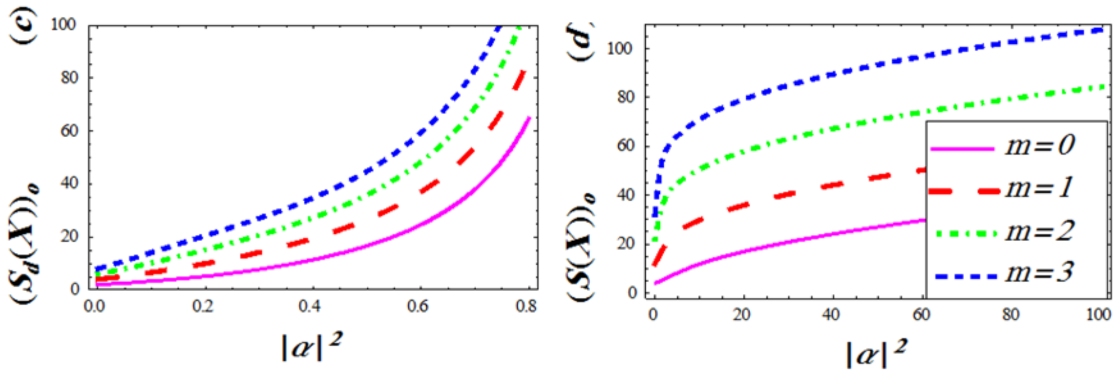


Figure 7: Diagrams of the squeezing versus $|\alpha|^2$ for different values of m and fixed $\nu = 3$ for the OPANCSs in both of the classes associated with P-T potential.

In these plots which have been drawn for various values of m and fixed $\nu = 3$, in EPANCSs and in the dual class squeezing is remarkable that it can be a candidate for the representation of non-classical properties, especially in the even dual class for m=0 there is fully squeezing behavior while this feature is totally absent in the other component and also in the standard PACSs. So it can be inferred that they can exhibit classical behavior in the region. On the other hand by considering this property for the odd class it is obvious that like the previous class just in the dual set there is squeezing and in the others no squeezing is seen.

Summary and conclusions

In this paper a new kind of EPANCSs and OPANCSs introduced and it was shown that if these states are to be called CSs they should satisfy the realization of the resolution of identity property as an important necessity. On the other hand statistical properties were considered through a function called P-T potential, like Mandel's Q parameter, second order correlation function and squeezing. In the Mandel parameter for odd class it was seen that for all values of m they obey from Sub-Poissonian statistics which was the same behavior in the even dual class but m=0 was the only exception with classical behavior. The interesting point for dual class emerged when the second order correlation function was considered in which in the odd class bunching effect was seen while in the standard photon added CSs anti bunching effect was visible. The same scenario was performed for the odd class too in which the behavior was totally anti bunching. Finally in the squeezing effect in the standard PACSs there was no squeezing in plotting the diagrams for different values of m and fixed $\nu = 3$ in both of the S(X) and S(P) components in which this was in contrast with the dual class that the squeezing existed. This statistical property was also plotted for different values of ϕ. As it was shown just for $\phi = 0$ in S(P) and $\phi = \frac{\pi}{2}$ in S(X) for dual classes squeezing effects appeared.

Appendix

The mean values that emerged in the statistical properties of the operators in the EPANCSs and OPANCSs can be easily calculated as follows,

$$\langle a \rangle_e = \langle \overline{a^\dagger} \rangle_e = 0 \quad (18\text{-a})$$

$$\langle a \rangle_o = \langle \overline{a^\dagger} \rangle_o = 0 \quad (18\text{-b})$$

$$\langle a \rangle_e^d = \langle \overline{a^\dagger} \rangle_e^d = 0 \quad (18\text{-c})$$

$$\langle a \rangle_o^d = \langle \overline{a^\dagger} \rangle_o^d = 0 \quad (18\text{-d})$$

$$\langle a^2\rangle_e = \langle \overline{a^{\dagger 2}}\rangle_e = |C_e|^{-1}\alpha^2\sum_{n=0}^{\infty}\frac{|\alpha|^{4n}\,\Gamma(2n+m+3)}{(2n+2)(2n+1)\Gamma^2(2n+1)[f\ (2n)]![f\ (2n+2)]!} \quad \text{(19-a)}$$

$$\langle a^2\rangle_o = \langle \overline{a^{\dagger 2}}\rangle_o = |C_o|^{-1}\alpha^2\sum_{n=0}^{\infty}\frac{|\alpha|^{4n+2}\,\Gamma(2n+m+4)}{(2n+3)(2n+2)\Gamma^2(2n+2)[f\ (2n+1)]![f\ (2n+3)]!} \quad \text{(19-b)}$$

$$\langle a^2\rangle_e^d = \langle \overline{a^{\dagger 2}}\rangle_e^d = |C_e|^{-1}\beta^2\sum_{n=0}^{\infty}\frac{|\beta|^{4n}[f\ (2n)]![f\ (2n+2)]!\Gamma(2n+m+3)}{(2n+2)(2n+1)\Gamma^2(2n+1)} \quad \text{(19-c)}$$

$$\langle a^2\rangle_o^d = \langle \overline{a^{\dagger 2}}\rangle_o^d = |C_o|^{-1}\beta^2\sum_{n=0}^{\infty}\frac{|\beta|^{4n+2}[f\ (2n+1)]![f\ (2n+3)]!\Gamma(2n+m+4)}{(2n+3)(2n+2)\Gamma^2(2n+2)} \quad \text{(19-d)}$$

$$\langle a^\dagger a\rangle_e = |C_e|^{-1}\sum_{n=0}^{\infty}\frac{|\alpha|^{4n}(2n+m)!(2n+m)}{((2n)!)^2[f^{\ 2}(2n)]!} \quad \text{(20-a)}$$

$$\langle a^\dagger a\rangle_o = |C_o|^{-1}\sum_{n=0}^{\infty}\frac{|\alpha|^{4n+2}(2n+m+1)!(2n+m+1)}{((2n+1)!)^2[f^{\ 2}(2n+1)]!} \quad \text{(20-b)}$$

$$\langle a^\dagger a\rangle_e^d = |C_e|^{-1}\sum_{n=0}^{\infty}\frac{|\beta|^{4n}[f^{\ 2}(2n)]!(2n+m)!(2n+m)}{((2n)!)^2} \quad \text{(20-c)}$$

$$\langle a^\dagger a\rangle_o^d = |C_e|^{-1}\sum_{n=0}^{\infty}\frac{|\beta|^{4n+2}[f^{\ 2}(2n+1)]!(2n+m+1)!(2n+m+1)}{((2n+1)!)^2} \quad \text{(20-d)}$$

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