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SUB-POISSONIAN AND TOTAL NOISE OF QUANTUM FIELD IN EIGHT-WAVE MIXING PROCESS

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Abstract : We study a sub-Poissonian and total noise in degenerate Eight-wave mixing process. We establish the analytic expression of first-order and second-order squeezing in terms of total noise under short-time approximation in degenerate six-wave mixing process. It shows that higher-order squeezing allows a much larger fractional noise reduction than lower-order squeezing. The photon statistics of the pump mode in the process is investigated and found to be sub-Poissonian in nature. The effect of sub-Poissonian nature of an optical field in terms of total noise is also incorporated. We show that the depth of nonclassicality directly depends on the amount of total noise present in the system. This suggests that the more squeezed the state is, the greater is its total noise in the system.

Keywords : Sub-Poissonian, Noise, Eight-wave mixing

I. Introduction

The Sub -Possonian were introduced by Hollenhorst and Caves [1, 2], but they accepted after Walls' paper [3]. The first successful experiments on the generation and detection of squeezed states were reported in the middle of the 1980s [4–6]. Over the past decades, the squeezing [7-11] in quantized electro-magnetic fields has received a great deal of attention because of its wide applications in many branches of science and technology, especially for low noise fluctuation [12–14] with an application in high quality optical telecommunication [15], quantum cryptography [16, 17], and so on. A detailed review of squeezed states was presented by Dodonov et al. [18] and Anderson et al. [19]. The basic concept of squeezed light is the reduction of quantum fluctuations in one quadrature at the expense of increased fluctuations in other quadrature. It has been focused on theoretical as well as experimental interpretation in various nonlinear optical processes, such as harmonic generation [20, 21], multiphoton processes [22–25], Raman process [26–28], hyper-Raman process [29], Hong and Mandel [30, 31], Hillery [32–34] and Zhan [35] for improving the performance of optical devices in communication network. Squeezing and photon statistics of the field amplitude in various nonlinear optical processes has also been reported by Perina [36]. Higher-order sub-poissonian of light has also been studied by Kim and Yoon [37]. Recently, Prakash and Mishra [38, 39] have reported the higher-order sub-poissonian photon statistics and their detection. An idea of experimental detection of nth- amplitude squeezing has been proposed by Prakash and Yadav [40]. Schumaker [41] has been introduced the concept of total noise in a quantum state. Further, the notion of total noise in relation to squeezing of a field state has been given by Hillery [42] that reported about the measurement of the size of the field amplitude fluctuations of a state of the field. Furthermore, Gupta et.al [43] and Gill et.al [44] has also been stated that the squeezing and total noise present in quantum state can be adjusted by varying the phase angle.

The chapter is organized for studying sub-poissonian and total noise in degenerate Eight-wave mixing process as follows: Section 1.2 gives definition of sub-poissonian and total noise of a quantum field state. The higher-order squeezing and sub-poissonian behaviour of light in terms of total noise are also incorporated in this section. Finally, we conclude this chapter in Section 2.4.

1. Definition sub-poissonian and total noise of a quantum field state

The notion of total noise of quantum state for a single mode can be defined [42] in terms of the operators which corresponds to real and imaginary parts of the field amplitude respectively

$$X_1 = \frac{1}{2}\left(A + A^{\dagger}\right) \quad \text{and} \quad X_2 = \frac{1}{2i}\left(A - A^{\dagger}\right) \tag{2.1}$$

where A≡ A(t) and $A^\dagger$≡ $A^\dagger$(t) are the varying operators. For a single mode of the field with frequency and creation (annihilation) operators $a^\dagger(a)$, they are given by

$$\mathrm{A(t)} = a(t)\exp(\mathrm{i}\omega t) \text{ and } \mathrm{A}^\dagger(t) = a^\dagger(t)\exp(-\mathrm{i}\omega t).$$

From equation (5.1), we find that

$$\left\langle X_1^2\right\rangle + \left\langle X_2^2\right\rangle = \left\langle N + \tfrac{1}{2}\right\rangle \tag{2.2}$$

The total noise, which is measure of the total fluctuations of the amplitude, is

$$T(\rho) = \langle \Delta X_1\rangle^2 + \langle \Delta X_2\rangle^2 \tag{2.3}$$

The uncertainty relation for X_1 and X_2 is

$$\Delta X_1 \Delta X_2 \geq \frac{1}{4} \tag{2.4}$$

which gives the condition for total noise as

$$T(\rho) \geq \langle \Delta X_1\rangle^2 + \frac{1}{\langle 4\Delta X_1\rangle^2} \tag{2.5}$$

Similarly Amplitude –squared squeezing is exist if

$$(\Delta \mathrm{Y}_1)^2 < \left\langle N + \frac{1}{2}\right\rangle \tag{2.6}$$

The fact increased nonclassicality gives rise to increase in the total noise [42, 43], can be verified by associating total noise with higher-order squeezing.

Using Hillery's approach [42] to relate the total noise to the uncertainty relations for the quadrature variables as follows

$$T_N = (\Delta X_1)^2 + (\Delta X_2)^2 \geq \frac{\left\langle N + \frac{1}{2}\right\rangle}{\left[4(\Delta Y_1)^2 + 1\right]} \tag{2.7}$$

From equation (5.12), it clears that for fixed $\langle N\rangle$, the total noise must increase as ΔY_1 decreases. Total noise (T_N) increases in the quantum state and becomes more squeezed. Hence it may be considered for measuring the depth of nonclassicality.

A state is sub-poissonian if

$$(\Delta N)^2 < \langle N\rangle$$

where.

$$N = A^\dagger A \quad \text{and } (\Delta N)^2 = \left\langle (N - \langle N\rangle)^2\right\rangle$$

In order to relate number operator to the total noise of quantum state, let us use Schwartz inequality,

$$\left|\langle (X_1 - \langle X_1\rangle)(N - \langle N\rangle)\rangle\right|^2 \leq \left\langle (X_1 - \langle X_1\rangle)^2\right\rangle \left\langle (N - \langle N\rangle)^2\right\rangle \leq (\Delta X_1)^2 (\Delta N)^2 \tag{2.8}$$

This implies that

$$(\Delta X_1)^2(\Delta N)^2 \geq \left|\langle (X_1 - \langle X_1\rangle)(N - \langle N\rangle)\rangle\right|^2 \geq \frac{1}{4}\left|\langle [X_1, N]\rangle\right|^2 \geq \frac{1}{4}\left|\langle X_2\rangle\right|^2 \tag{2.9}$$

where $[X_1, N] = iX_2$

Similarly,

$$(\Delta X_2)^2(\Delta N)^2 \geq \frac{1}{4}\left|\langle X_1\rangle\right|^2 \tag{2.10}$$

From equations (5.14) and (5.15), we have

$$4(\Delta N)^2[(\Delta X_1)^2 + (\Delta X_2)^2] \geq \langle X_1\rangle^2 + \langle X_2\rangle^2 \tag{2.11}$$

Using equation (5.2) and simplify, we get

$$[4(\Delta N)^2 + 1][(\Delta X_1)^2 + (\Delta X_2)^2] \geq \left\langle N + \frac{1}{2}\right\rangle \tag{2.12}$$

Therefore, the total noise in quantum state in terms of number operator is

$$T_N = [(\Delta X_1)^2 + (\Delta X_2)^2] \geq \frac{\left\langle N + \frac{1}{2}\right\rangle}{[4(\Delta N)^2 + 1]} \tag{2.13}$$

From equation (2.13) it is clear that, the total noise must increase as $(\Delta N)^2$ decreases.

2.3 Sub-poissonian and total noise in fundamental mode in DSWM process

The process in this model, involving absorption of three pump photons having frequency ω_1 each and emission of two probe photons (stokes) with frequency ω_2 each. The atomic system finally returns to ground state by emitting one signal photon of frequency ω_3 as shown in Figure 5.1.

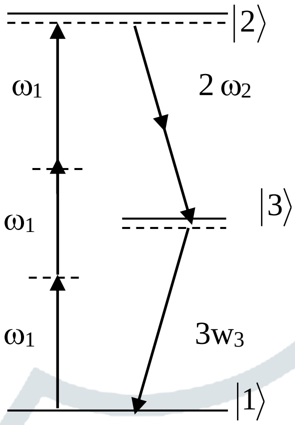

Figure 1: Degenerate Eight-wave interaction model [45]

The Hamiltonian of this model is $(\hbar = 1)$

$$H = \omega_1 a^\dagger a + \omega_2 b^\dagger b + \omega_3 c^\dagger c + g\left(a^3 b^{\dagger 2} c^{\dagger 3} + a^{\dagger 3} b^2 c^3\right) \tag{2.14}$$

where $a^\dagger(a)$, $b^\dagger(b)$ and $c^\dagger(c)$ are the creation (annihilation) operators of $A = a\exp(i\omega_1 t)$, $B = b\exp(i\omega_2 t)$ and $C = c\exp(i\omega_3 t)$, associated with the relation $3\omega_1 = 2\omega_2 + 3\omega_3$ respectively and g is the coupling constant between the two modes per second.

The Heisenberg equation of motion for mode A is

$$\dot{A} = \frac{\partial A}{\partial t} + i[H, A] \tag{2.15}$$

Using (2.14) in (2.15), we obtain

$$\dot{A} = -3igA^{\dagger 2}B^2C^3 \tag{2.16}$$

Similarly, we obtain the relations for $\dot{B}$ and $\dot{C}$ as

$$\dot{B} = -2igA^3B^\dagger C^\dagger \quad \text{and} \quad \dot{C} = -igA^3B^{\dagger 2} \tag{2.17}$$

Using Taylor's series for expanding A(t) and retaining up to $|gt|^2$, we obtain

$$\dot{A}(t) = A - 3igtA^{\dagger 2}B^2C + \frac{3}{2}g^2t^2 \times (6A^\dagger A^2B^{\dagger 2}B^2C^\dagger C + 6AB^{\dagger 2}B^2C^\dagger C - 4A^{\dagger 2}A^3B^\dagger BC^\dagger C$$
$$- 2A^{\dagger 2}A^3C^\dagger C - A^{\dagger 2}A^3B^{\dagger 2}B^2 - 4A^{\dagger 2}A^3B^\dagger B - 2A^{\dagger 2}A^3) \tag{2.18}$$

The real quadrature component in fundamental mode A is given as

$$X_{1A}(t) = \frac{1}{2}\left[A(t) + A^\dagger(t)\right] \tag{2.19}$$

$$[\Delta X_{1A}(t)]^2 - \frac{1}{4} = -3g^2t^2|\alpha|^4 \cos 2\theta \tag{2.20}$$

where θ is the phase angle, with $\alpha = |\alpha|e^{i\theta}$ and $\alpha^* = |\alpha|e^{-i\theta}$

we assume quantum state as a product of coherent states |⟨> for the fundamental mode A, |®> for the Stokes mode B and vacuum state |0> for the mode C,

$$|\psi\rangle = |\alpha\rangle_A |\beta\rangle_B |0\rangle_C \tag{2.21}$$

Therefore We obtain,

$$[\Delta X_{1A}(t)]^2 - \frac{1}{4} = -\frac{3}{2}g^2t^2|\alpha|^4(|\beta|^4 + 4|\beta|^2 + 2)\cos 2\theta, \tag{2.22}$$

Further the total noise in this process can be measured as

$$(T_N)_x \geq [\Delta X_{1A}(t)]^2 + \frac{1}{4[\Delta X_{1A}(t)]^2} \geq \frac{1}{4} - 3g^2t^2|\alpha|^4 \cos 2\theta + \frac{1}{1-12g^2t^2|\alpha|^4 \cos 2\theta} \qquad (2.23)$$

The expression on the left-hand side of the above inequality reaches a minimum when $\Delta X_1 = 1/2$. The value of ΔX_1 indicates the classical region. For

$0 < \Delta X_1 < 1/2$, as ΔX_1 decreases T_N increases.

For second-order squeezing, the real quadrature component of the fundamental mode is expressed as

$$[\Delta Y_{1A}(t)]^2 = \langle Y_{1A}^2(t)\rangle - \langle Y_{1A}(t)\rangle^2$$

$$= \frac{1}{4}[4|\alpha|^2 + 2 - 24g^2t^2(\alpha^4|\alpha|^2 + \alpha^4 + \alpha^{*4}|\alpha|^2 + \alpha^{*4} + 4|\alpha|^6 + 9|\alpha|^4 + 3|\alpha|^2] \qquad (2.24)$$

Using equation (2.24) and then the number of photon in mode A may be expressed as

$$N_{1A}(t) = A^\dagger(t)A(t) = A^\dagger A - 6g^2t^2 A^{\dagger 3}A^3 \qquad (2.25)$$

Then, we have

$$\left\langle N_{1A}(t) + \frac{1}{2}\right\rangle = \left[|\alpha|^2 + \frac{1}{2} - 6g^2t^2|\alpha|^6\right] \qquad (2.26)$$

Subtracting (5.41) from (5.39), we get

$$[\Delta Y_{1A}(t)]^2 - \left\langle N_{1A}(t) + \frac{1}{2}\right\rangle = -6g^2t^2\left\{2\cos 4\theta\left(|\alpha|^4 + |\alpha|^6\right) + 3|\alpha|^6 + 9|\alpha|^4 + 3|\alpha|^2\right\} \qquad (2.27)$$

Using condition (2.27), we obtain

$$[\Delta Y_{1A}(t)]^2 - \left\langle N_{1A}(t) + \frac{1}{2}\right\rangle = -3g^2t^2\left\{2\cos 4\theta\left(|\alpha|^4 + |\alpha|^6\right) + 3|\alpha|^6 + 9|\alpha|^4 + 3|\alpha|^2\right\}(|\beta|^4 + 4|\beta|^2 + 2) \qquad (2.28)$$

Further the total noise in terms of second-order squeezing,

$$(T_N)_y \geq \frac{\left\langle N_{1A}(t) + \frac{1}{2}\right\rangle}{4[\Delta Y_{1A}(t)]^2 + 1}$$

$$\geq \frac{|\alpha|^2 + \frac{1}{2} - 6g^2t^2|\alpha|^6}{4|\alpha|^2 + 3 - 24g^2t^2\left\{(|\alpha|^4 + |\alpha|^6)2\cos 4\theta + 4|\alpha|^6 + 9|\alpha|^4 + 3|\alpha|^2\right\}} \qquad (2.29)$$

Equation (2,28), shows that for fixed $\langle N\rangle$, the total noise must increase as $[\Delta Y(t)]^2$ decreases.

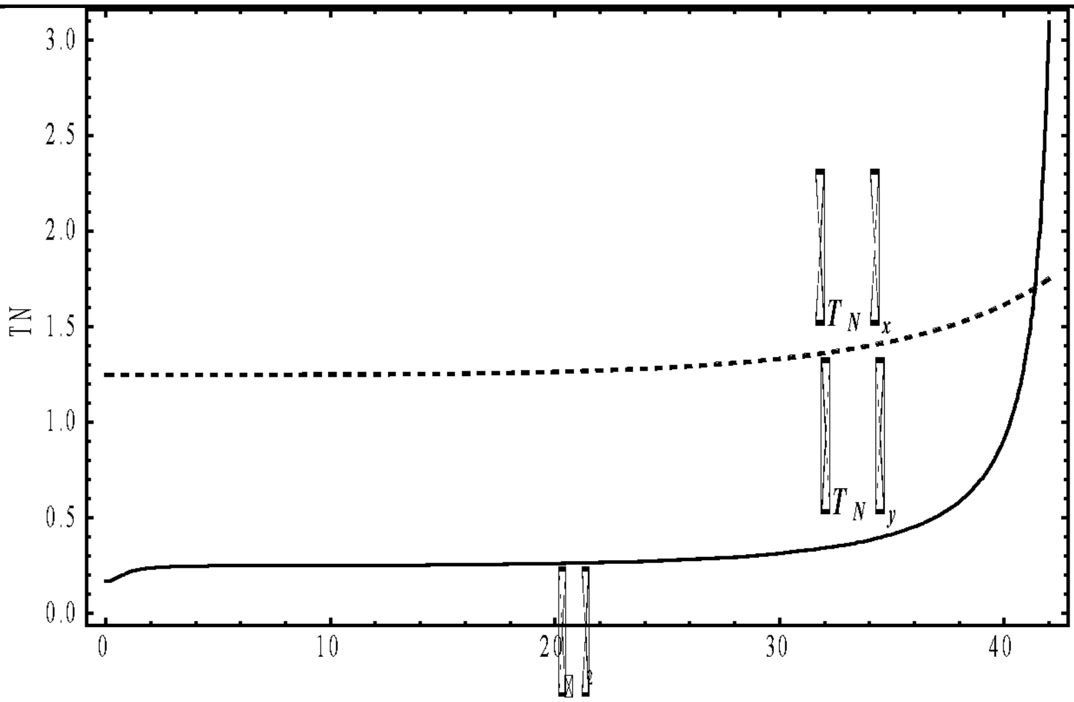

Figure 2: Variation of Total noise (T_N) **in quantum state with** $|\alpha|^2$ **(when** $|gt|^2 = 10^{-8}$ **and** $\theta = 0)$ **(dashed line: first-order** $(T_N)_x$ **and solid line: second-order** $(T_N)_y$

The variation of second-order squeezing in terms of total noise with $|\langle|^2$ is shown in figure 2. For $|\beta|^2 = 0$ corresponds to spontaneous process. The steady raise of the curves (figure 2) shows the total noise increases with increase of the number of photons ($|\langle|^2$). It infers that the depth of nonclassicality directly depends on the large number of photons. This also suggests that the more squeezed the state is, the greater is its total noise.

A comparison between figures shows greater total noise and hence greater squeezing in second-order than in first-order, having same number of photons.the maximum total noise is possible in higher-order (second-order) squeezing. It again infer that the more squeezed the state is, the greater is its total noise.

Using (2.25) and (2.27), the sub-Poissonian photon statistics in the fundamental mode is

$$[\Delta N_{1A}(t)]^2 - \langle N_{1A}(t)\rangle = -30g^2t^2|\alpha|^6 \tag{2.30}$$

For studying sub-Poissonian photon statistics behaviour, let us plot a sketch between **S_n** and $|\langle|^2$ as shown in figure 3.

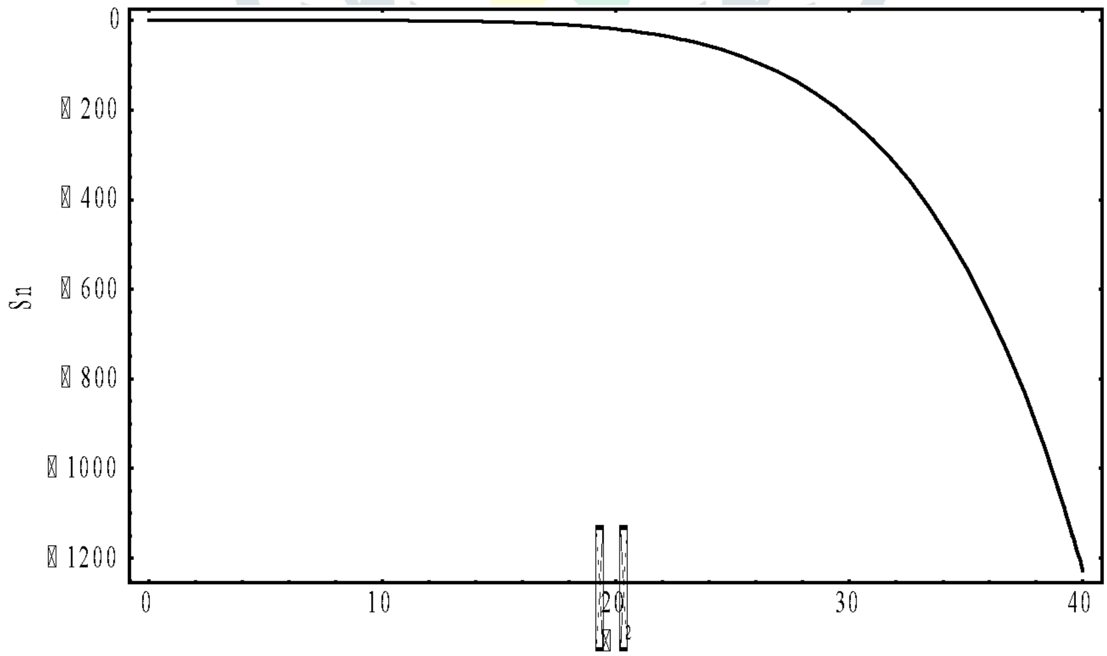

Figure 3: Variation of sub-poissonian states (S_n) with $|\alpha|^2$ **(when** $|gt|^2 = 10^{-8}$ **and** $\theta = 0)$

The figure 2 show that the sub-poissonian statistics properties of light is directly proportional to the number of photons i.e. sub-poissonian statistics of light increases with increasing $|\langle|^2$. Thus, the degree of sub-poissonian photon statistics is also associated with large number of photons.

Hence, the total noise related to number operator,

$$(T_N)_n \geq \frac{\left\langle N_{1A}(t)+\frac{1}{2}\right\rangle}{4[\Delta N_{1A}(t)]^2+1} \geq \frac{|\alpha|^2+\frac{1}{2}-6g^2t^2|\alpha|^6}{4|\alpha|^2+1-144g^2t^2|\alpha|^6} \tag{2.30}$$

From above equation (2.30), it is evident that for fixed $\langle N\rangle$ as $[\Delta N(t)]^2$ decreases, then T_N must increases. The variation of total noise in terms of number operator $(T_N)_n$ with |⟨|² is shown in figure 4. The steady raise of the curve (figure 3) shows the total noise increases with increase of the number of photons |⟨|². Therefore, as state becomes more sub-poissonian $\left[\Delta N(t)/\langle N\rangle = \text{decreasing}\right]$ as its total noise increases.

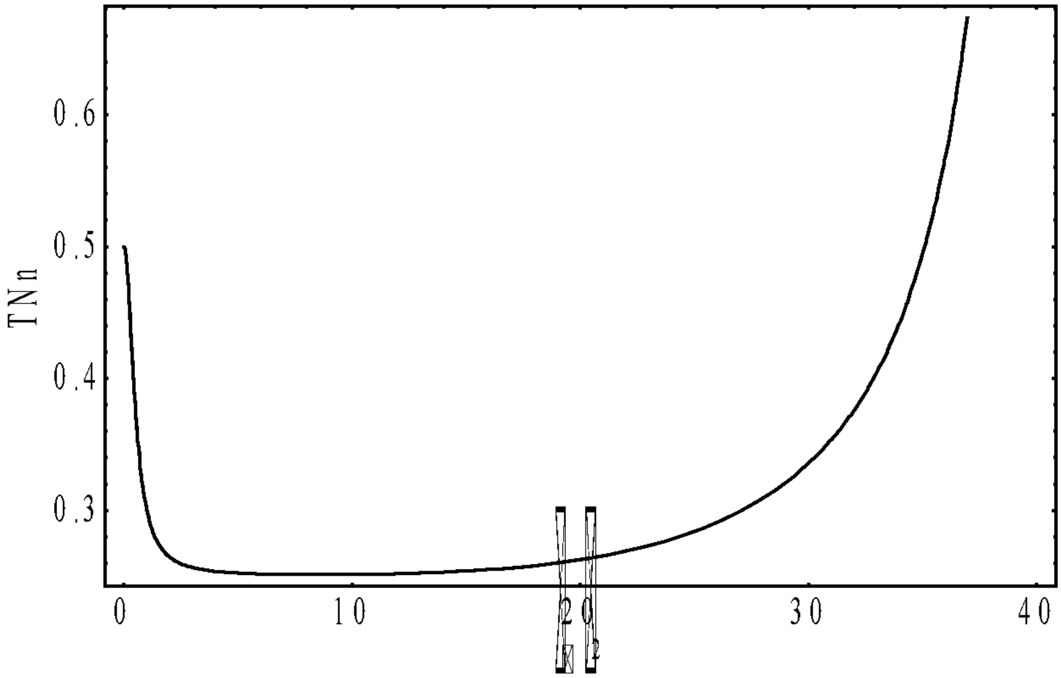

Figure 4: Variation of Total noise $(T_N)_n$ in sub-poissonian state with $|\alpha|^2$

(when $|gt|^2=10^{-8}$ and $\theta=0$)

2.4 CONCLUSIONS

In this chapter It is shown that greater total noise and hence greater squeezing exist in second-order than in first-order, having same number of photons. The result agrees with the result of Hillery [42]. Hence the maximum total noise is possible in higher-order squeezing. It is inferred that the more squeezed the state is, the greater is its total noise in the system. It is also found that total noise increases in the quantum state and becomes more squeezed state. Hence it may be considered for measuring the depth of nonclassicality of any quantum state.

It is shown that the sub-poissonian statistical properties of light is directly proportional to number of photons of the fundamental mode i.e. sub-poissonian states of light increases with increasing |⟨|². It is found that the total noise increases with increase of the number of photons |⟨|². Therefore, as state becomes more sub-poissonian and its total noise increases.

These results suggest that the desired degree of squeezing, sub-poissonian and total noise can be obtained by using short interaction time and number of photons present in the radiation field before interaction in the system. Hence, the total noise of a quantum state can be measured the depth of nonclassicality i.e. more nonclassical a state (squeezing and sub-poissonian) of the field in any system.

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