Photon antibunching of pulsed squeezed light

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Abstract

We observed the phenomenon of photon antibunching for squeezed coherent states,
which are generated via parametric amplification pumped by cw mode-locked pulses.

1. INTRODUCTION

Nonclassical properties of the quadrature squeezed light have been thus far demonstrated
by measuring the noise level below the shot noise limit[1]. Another important manifestation of nonclassical nature of light is the phenomenon of photon antibunching[2].
Theoretically D. Stoler pointed out a possibility to observe this phenomenon by using a
degenerate parametric amplifier in 1974[3]. However this has been demonstrated only in
the resonance fluorescence from a system of very small number of atoms[4].

In the present study we have performed an experiment to show the nonclassical nature
of the squeezed light by measuring the second order correlation function (intensity correlation). This is proportional to the probability of a second photon being detected at the
time \( \tau \) after a first one. The squeezed coherent light is generated in a parametric amplifier
pumped by the second harmonic of a cw mode-locked laser light. When two photons are
simultaneously absorbed in parametric process, intensity correlation for \( \tau = 0 \) decreases
(antibunching). On the other hand when two photons are simultaneously emitted it increases (bunching). The direction of the energy flow between the input fundamental field
at frequency \( \omega \) and the second harmonic field at frequency \( 2\omega \) depends on the relative
phase of the two fields. So both antibunching and bunching can be realized by changing
the relative phase. In our experiment we used pulsed light in order to obtain a large
parametric gain even from a single-pass parametric amplifier[5]. The observed intensity
correlation function consists of peaks at the intervals of the mode-locked laser. The number
of coincidence counts at \( \tau = 0 \) became below or above those at large enough \( \tau \). This
is the first report, to our knowledge, on the observation of antibunching for quadrature
squeezed light generated by parametric amplification.
2. EXPERIMENTAL APPARATUS

Fig.1 shows our experimental apparatus used to observe antibunching. A cw mode-locked Nd:YAG laser (Spectron model ML903) generates IR pulses with FWHM $\sim$100psec at a repetition rate of 82MHz. Second harmonic light (2$\omega$) is generated in LiB$_3$O$_5$ crystal and is used to pump a single-pass parametric amplifier (PA). The residual IR pulses are attenuated by harmonic mirrors and used as an input signal ($\omega$) for PA.

A collinear configuration is chosen to stabilize the relative phase between the signal ($\omega$) and the pump (2$\omega$). Precise adjustment of intensity of the signal and the pump and their relative phase ($\varphi$) is essential to observe antibunching. Two harmonic wave plates (HWP), a polarizer (P) and a birefringent filter (BRF) are used for this adjustment. A combination of two HWP, which work as half-wave plate for the signal and as full-wave plate for the pump, and a polarizer is used as a variable attenuator for the signal. The change of the polarization direction is shown at the top of Fig.1. BRF (thickness of 0.7mm) is used to control the relative phase. The polarization of the signal and the pump are perpendicular to each other and the crystal axis of BRF is perpendicular to the polarization of the pump. So by changing the incidence angle to the BRF, the refractive index of the signal varies (extraordinary ray), while that of the pump remains constant (ordinary ray).

M1 consists of dielectric mirrors which reflect only IR light. Extremely weak IR light ($\sim 10^{-11}$W) is used as a signal for PA (Ba$_2$NaNb$_5$O$_{15}$ crystal). After amplification the pump (2$\omega$) is eliminated by using a mirror and filters (HOYA IR83) which are indicated by M2 in Fig.1. The squeezed vacuum (parametric fluorescence) component, which is strongly bunched, also exists at the frequency region where we do not have input signal components. In order to remove such fluorescence an etalon and an interference filter are used to restrict the observed frequency bandwidth.

Photon counting is performed by two silicon avalanche photodiodes (APD) (RCA model SPCM-100-PQ, $\eta$@1.06$\mu$m $\sim$6.8%). A time-to-amplitude converter (TAC, TENNELEC) is used to measure the intensity correlation.

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**Fig.1** Schematic drawing of experimental apparatus
3. EXPERIMENTAL RESULTS

The intensity correlation observed by the coincidence counting is shown in Fig. 2-4 as a function of the time-delay. They show peaks at 12nsec intervals corresponding to the repetition rate of the mode-locked laser. The width of the peak is due to the resolution time of the APD. The actual response time of the detection is determined by the laser pulse width.

The total number of counts in a single peak is shown above each peak. These numbers correspond to the intensity correlation function $G^{(2)}(\tau)$ defined as:

$$G^{(2)}(\tau) = \langle a^\dagger(t)a^\dagger(t+\tau)a(t+\tau)a(t) \rangle.$$  \hspace{1cm} (1)

When $\tau$ is sufficiently large, there are no correlations between photons at time $t$ and those at time $t+\tau$. So $G^{(2)}(\tau)$ reduces to

$$G^{(2)}(\tau) \rightarrow \langle a^\dagger(t)a(t) \rangle \langle a^\dagger(t+\tau)a(t+\tau) \rangle. \hspace{1cm} (\tau \gg 1)$$

The normalized intensity correlation $g^{(2)}$ is defined as:

$$g^{(2)}(\tau) = \frac{\langle a^\dagger(t)a^\dagger(t+\tau)a(t+\tau)a(t) \rangle}{\langle a^\dagger(t)a(t) \rangle^2}. \hspace{1cm} (2)$$

The denominator is calculated by averaging the total number of counts for peaks at $\tau = -12, 12, 24, \ldots, 72$ nsec.

In Fig. 2 and Fig. 3 experimental results obtained under the same condition except for the relative phase $\varphi$ are shown. The squeezing parameter $r$ is 0.07 estimated from the counted numbers shown in Fig. 2 and 3, when the average power of the pump is about 150mW. The input intensity of the signal is estimated to be 0.96 photon/pulse using the quantum efficiency of APD, etc. The relative phase (incidence angle to BRF) was chosen so that the output power of the parametric amplifier became either minimum or maximum. The value of $g^{(2)}$ changes below and above unity when the relative phase is varied: $g^{(2)} = 0.96 \pm 0.006$ and $g^{(2)} = 1.13 \pm 0.04$, respectively. Fig. 2 unmistakably indicates that the squeezed coherent state exhibits the phenomenon of antibunching, which is understandable only in terms of quantized electromagnetic field.

The result shown in Fig. 4 was obtained when the input-signal intensity was reduced to the weakest limit. In this case $g^{(2)}$ was always larger than 2 independent of $\varphi$.

Fig. 2 Input number of photons ~ 0.96/pulse. $r = 0.07, \varphi \sim 0, g^{(2)} = 0.965 \pm 0.006$. 

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4. DISCUSSION

In this section we compare the experimental result with a simple theory. First we describe the normalized intensity correlation of a single-mode squeezed coherent state, $|\alpha, \zeta \rangle$. This is defined as[7]

$$|\alpha, \zeta \rangle \equiv \mathcal{S}(\zeta) \mathcal{D}(\alpha) |0 \rangle, \quad \mathcal{D}(\alpha) \equiv \exp(\alpha a^\dagger - \alpha^* a), \quad \mathcal{S}(\zeta) \equiv \exp(\frac{1}{2} \zeta^* a^2 - \frac{1}{2} \zeta a^\dagger a) \quad (3)$$

where $\mathcal{D}$ is a displacement operator and $\mathcal{S}$ is a squeezing operator, $\alpha$ is a complex amplitude of a coherent state, $\zeta$ is a complex squeezing parameter. This definition corresponds to our experimental procedure that the squeezed light is produced by parametric amplification of laser light. The normalized intensity correlation function for this state is

$$g^{(2)}(|\alpha|^2, r, \varphi) = \frac{\sinh^2 r (3 (\sinh^2 r) + 1) + 4|\alpha|^2 \sinh^2 r (\cosh 2r - \cos \varphi \sinh 2r)}{\sinh^2 r + |\alpha|^2 (\cosh 2r - \cos \varphi \sinh 2r)^2}$$

$$+ \frac{-|\alpha|^2 \sinh 2r (\cos \varphi \cosh 2r - \sinh 2r) + |\alpha|^4 (\cosh 2r - \cos \varphi \sinh 2r)^2}{\sinh^2 r + |\alpha|^2 (\cosh 2r - \cos \varphi \sinh 2r)^2} \quad (4)$$
where \( r \equiv |\zeta| \) and \( \varphi \equiv 2 \arg \alpha - \arg \zeta \), which is the relative phase between the input coherent field and the pump.

Antibunching occurs for \( \varphi = 0 \), so \( g^{(2)}(|\alpha|^2, r, \varphi) \) for \( \varphi = 0 \) is shown in Fig.5. \(|\alpha|^2\) corresponds to input photon number and \( r \) is the squeezing parameter. For a fixed \(|\alpha|^2\) this function takes the minimum value at \( r \) where \(|\alpha|^2 = \frac{1}{2} \exp(4r) \sinh 2r \), and \( \lim_{|\alpha|^2, r \to 0} g^{(2)}(|\alpha|^2) = \frac{1}{2} \exp(4r) \sinh 2r, \varphi = 0 \) = 0. Note that this function is singular at \((|\alpha|^2, r) = (0, 0)\) because \( g^{(2)}(\forall |\alpha|^2, r = 0, \varphi = 0) = 1 \) and \( \lim_{r \to 0} g^{(2)}(|\alpha|^2 = 0, r, \varphi = 0) = \lim_{r \to 0} 3 + \frac{1}{\sinh 2r} = \infty \). However, this point cannot be observed because there exists no photons when \(|\alpha|^2 = r = 0\).

In the experiment the intensity correlation is measured for different relative phases while the input-signal intensity and parametric gain is fixed. \( g^{(2)}(|\alpha| = 0.96, r = 0.07, \varphi) \) is shown in Fig.6.

**Fig.5** Normalized intensity correlation as a function of \(|\alpha|^2\) and \( r \) for \( \varphi = 0 \).

**Fig.6** Normalized intensity correlation as a function of \( r \) for \(|\alpha|^2 = 0.96 \) and \( r = 0.07 \).

Measured \( g^{(2)} \) (0.97 for \( \varphi \sim 0 \), 1.13 for \( \varphi \sim \pi \)) is consistent with the prediction of the simple theory \( g^{(2)} = 0.86 \) for \( \varphi = 0 \), \( g^{(2)} = 1.15 \) for \( \varphi = \pi \), see Fig.2-3). Fig.5 shows that a smaller value of \( g^{(2)} \) for \( \varphi \sim 0 \) should be observed if we use a weaker input-signal intensity for the same parametric gain. However, the measured value of \( g^{(2)} \) for this weaker input is larger than what is shown in Fig.2. This is mainly due to the effect of parametric fluorescence components, which is strongly bunched. The bandwidth of the input signal is about 4GHz and that of the etalon is about 50GHz. So, as shown in Fig.7, the observed fields are composed of the squeezed coherent component and the fluorescence component; the phase matching condition of parametric process is relatively broad compared to the bandwidth of the etalon.

Thus, when the input-signal intensity is weak, the contribution of strongly bunched fluorescence becomes relatively large, and the amount of antibunching is reduced.
5. CONCLUSION

Photon antibunching of squeezed coherent states generated by parametric amplification was observed for the first time to our knowledge. Both antibunching and bunching were observed by changing the relative phase between the input-signal and the pump. The amount of antibunching observed is reduced by the existence of parametric fluorescence which could not be eliminated effectively by the etalon used. A more detailed theoretical analysis and an improved experiment are now in progress.

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References


