Optoelectronics in Suppression Noise of Light

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1. Introduction

High quality light, whenever coherent light and nonclassical light, is more and more widely used in many filed. The coherent state behave minimum classical noise and better coherence, is mostly important light in quantum information, precise measurement and quantum metrology etc. In quantum information and quantum optics, a coherent light is used to entanglement generation (Ou, Z. et al. 1992), quantum teleportation (Furusawa, A. et al. 1998), quantum computation (Menicucci, N. et al. 2006) and quantum secret sharing (Lance, A. et al. 2004). The quiet laser beam, shot noise limited laser beam is important in above application.

In the past 20 years there has been much interest in the generation and application of various nonclassical light sources, such as squeezed-state entanglement, quantum-correlated twin beams, and sub-poissonian light, for which improved signal-to-noise ratios and measurement precision beyond the quantum-noise limit are anticipated. In particular, sub-poissonian light is a promising light source in quantum information and optical communication because of its communication capacity (Tapster, P. et al. 1988; Teich, M. & Saleh, B. 1985; Machida, S. et al. 1987,1989; Richardson, W. et al. 1991; Li, R. et al. 1995).

In 1990 Mertz et al. (Mertz, J. et al. 1990) obtained sub-Poissonian light by using the feed-forward technique, and in the year of 1997, P. K. Lam et al. (Lam, P. et al. 1997) experimental demonstrate noiseless signal amplification of using positive optoelectronic feed forward. The technique of optoelectronics is applied into noise suppression of light and noiseless signal amplification, and it is extended to other displacement transformation, such as quantum teleportation (Furusawa, A. et al. 1998), quantum cloning (Andersen, U. 2005; Braunstein, S. et al. 2001); furthermore, the purification of nonclassical light recently (Hage, B. et al. 2008; Dong, R. et al. 2008).

In this paper, we introduce the application of opto-electronics in noise suppression. It includes two parts, section II is noise suppression of fiber laser to SNL by optoelectronic feed forward and section III is preparation of sub-poissonian state by opto-electronic feedforward.

2. Suppression intensity noise of fiber laser

As we all known, a general laser beam is near the coherent light, the fiber laser is the new type laser, it behave some advantageous: high output power, small size and good frequency stability, easy to coupled with the fiber, but the light is not complete coherent light,

especially at the low sideband frequency, the light have higher noise than shot noise limit (SNL). It hinders fiber laser application in the quantum information, so suppression the noise of fiber laser is a significant issue. Intensity noise of fiber laser include beating noise, environmental perturbations, thermal noise, and fluctuations in pump power (Cheng, Y. et al. 1995).Various methods for partially reducing output noise have been proposed. High frequency beating noise from fiber ring laser can be reduced by intracavity spectral filtering (Sanders, S. et al.1992). Intensity noise of fiber laser at the relaxation oscillation frequency was suppressed by integrating a negative feedback circuit (Spiegelberg, C. et al. 2004; Ball, G. et al. 2008).

Optoelectronic feed forward, which is easy and practical, is a method to suppression noise of light easily. In the section we introduce an optoelectronic feed-forward loop used to suppress the intensity noise of the fiber laser. Selecting the best delay time and feed-forward gain, the intensity noise can be suppressed near to SNL at sideband frequency. The maximum noise reduction 22dB was obtained at 6.0MHz. Furthermore, altering the delay time and filter band of optoelectronic system, the light can near to shot noise at differ frequency point. After the noise suppression, the fiber laser can be widely applied into the filed of quantum information.

The experiment setup of laser noise suppression is shown in fig.1. It is based on the noise correlation between reflection light and transmission light.
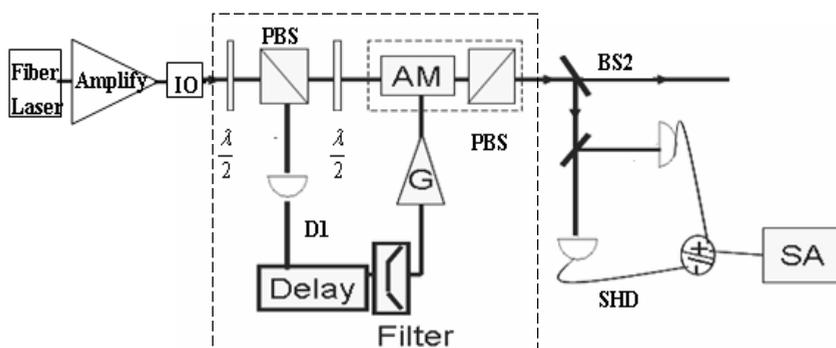

Fig. 1. The experiment setup of suppression of intensity noise of fiber laser with OptoElectronic feedforward. PBS: polarization beam splitter; BS: beam splitter; AM: amplitude modulator; D1; detector; SHD: homodyne detectors; SA: spectrum analyzer.

As shown in fig.1, the laser output from fiber laser is divided into two parts by beam splitter which is composed by polarization beam splitter (PBS) and half wave plate. The detector D1 detects the reflected light and the measurement of D1 is taken as the signal of feed forward. After passed through delay, filter and amplifier, the signal is acted on amplitude modulator (AM). As the result, the noise of transmission is suppressed, and the noise is measured by homodyne detectors.

2.1 Theory of optoelectronic feed forward in noise suppression

The output field of fiber laser can be expressed:

$$\hat{A}_{in}(t) = A_{in} + \delta\hat{A}_{in}(t) \tag{1}$$

Here, $\hat{A}_{in}(t)$ is the annihilate operator of input field, A_{in} is the average value of input field, $\delta\hat{A}_{in}(t)$ is fluctuation of input field.

After passed through AM, the light field can read as (Lam, P. et al. 1997):

$$\hat{A}_{out}(t) = \sqrt{\eta_3}[\sqrt{1-R}A_{in} + \sqrt{1-R}\delta\hat{A}_{in}(t) + \sqrt{R}\delta\hat{v}_1(t) + \delta\hat{r}(t)] + \sqrt{1-\eta_3}\delta\hat{v}_3(t) \qquad (2)$$

Where $\hat{v}_1$ is vacuum noise from the first BS; $\hat{v}_3$ is vacuum noise corresponding to imperfect of homdyne detector system, η_3 is the efficiency of homdyne detectors. $\delta\hat{r}$ is fluctuation from feedback loop; η_2 is efficiency of detector D1.

$$\delta\hat{r}(t) = \int_{-\infty}^{\infty}\kappa(\tau)\sqrt{R\eta_2} \times A_{in}[\sqrt{R\eta_2}\delta\hat{X}_{Ain}(t-\tau)$$
$$-\sqrt{(1-R)\eta_2}\delta\hat{X}_{v1}(t-\tau) + \sqrt{R}\delta\hat{X}_{v2}(t-\tau)]d\tau \qquad (3)$$

Here $\kappa(\tau)$ is response function of feedback loop; $\delta\hat{X}_{in} = \delta\hat{A}_{in} + \delta\hat{A}_{in}^+$, $\delta\hat{X}_{vi} = \delta\hat{A}_{vi} + \delta\hat{A}_{vi}^+$ are amplitude quadrature and phase quadrature, respectively.

The amplitude quadrature of output field can be deduced from ref. (1) and (2)

$$\delta\hat{X}_{out}(t) = \delta\hat{A}_{out}(t) + \delta\hat{A}_{out}^+(t)$$
$$= \sqrt{\eta_3}[\sqrt{1-R}\delta\hat{X}_{in}(t) + \sqrt{R}\delta\hat{X}_{\hat{v}_1}(t) + \delta\hat{X}_r(t)] + \sqrt{1-\eta_3}\delta\hat{X}_{\hat{v}_3}(t) \qquad (4)$$

Here

$$\delta\hat{X}_r(t) = \delta\hat{r}(t) + \delta\hat{r}^+(t)$$
$$= \int_{-\infty}^{\infty}G(\tau)[\sqrt{R\eta_2}\delta\hat{X}_{Ain}(t-\tau) - \sqrt{(1-R)\eta_2}\delta\hat{X}_{v1}(t-\tau) + \sqrt{R}\delta\hat{X}_{v2}(t-\tau)]d\tau$$

$$G(\tau) = \kappa(\tau)\sqrt{R\eta_2} \times A_{in}$$

The equation (4) can be easily solved by taking the Fourier transform into the frequency domain:

$$\delta\hat{X}_{out}(\omega) = \sqrt{\eta_3}\{\sqrt{1-R}\delta\hat{X}_{in}(\omega) + \sqrt{R}\delta\hat{X}_{\hat{v}_1}(\omega) + G(\omega)[\sqrt{R\eta_2}\delta\hat{X}_{in}(\omega)$$
$$-\sqrt{(1-R)\eta_2}\delta\hat{X}_{v1}(\omega) + \sqrt{R}\delta\hat{X}_{v2}(\omega)]\} + \sqrt{1-\eta_3}\delta\hat{X}_{\hat{v}_3}(\omega) \qquad (5)$$

Here G(ω) is the gain of feedback, $G(\omega) = \kappa(\omega)\sqrt{R\eta_2} \times A_{in}$.

We can obtain the noise spectrum of output filed:

$$V_{out}(\omega) = \left\langle \left|\delta X_{Aout}\right|^2 \right\rangle$$
$$= \eta_3\left|\sqrt{(1-R)} + G(\omega)\sqrt{R\eta_2}\right|^2 V_{in}(\omega) + \eta_3\left|\sqrt{R} - G(\omega)\sqrt{(1-R)\eta_2}\right|^2 V_1 \qquad (6)$$
$$+\eta_3\left|G(\omega)\sqrt{(1-\eta_2)}\right|^2 V_2 + (1-\eta_3)V_3$$

Here V_1, V_2, V_3 are vacuum noise spectrum and $V_1 = V_2 = V_3 = 1$; V_{in} is the intensity noise spectrum of input field.

To infer from eq.(6), when $G(\omega) = G(\omega)_{opt}$, the intensity noise suppression is best, and then the minimum output noise $V_{out}(\omega)$ is:

$$V_{out}^{opt}(\omega) = \frac{[R\eta_2 + (1-R)\eta_3](V_{in}(\omega)-1)+1}{(V_{in}-1)R\eta_2+1} \quad, \tag{7}$$

$$G(\omega)_{opt} = \frac{-(V_{in}-1)\sqrt{(1-R)R\eta_2}}{V_{in}R\eta_2 + \eta_2(1-R)+(1-\eta_2)} \quad, \tag{8}$$

When η_2=0.95, η_3=0.20, the optimum output noise V_{out}^{opt} as the function of input noise V_{in} and BS reflection R is shown in fig.2. With the same R, higher the input noise is, higher the output noise is, and with the same input noise, higher the reflection R is, lower the output noise V_{out} is. Just only when $R=1$, the output noise V_{out}^{opt} reach at shot noise limit (SNL). In general, the reflection R is always smaller than 1 in order to get effective intensity of output field, the method can suppress main noises, but not all noises.
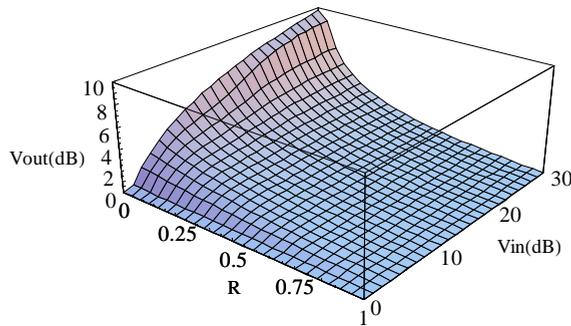

Fig. 2. The optimum output noise V_{out}^{opt} as the function of input noise V_{in} and BS reflection R, η_2=0.95, η_3=0.20.

2.2 Noise suppression

The relationship of residual output noise and reflection R is shown in fig. 3. at 6 MHz, the dot is experiment data; the dash line is theory result as eq. (7). The detector D1 can be in saturation when the R is high, we make $\eta_2 \times R = $ constant to correct the theory of dash line, and the solid line is the corrected theoretical result. In the experiment, $\eta_2 = 0.95$, C=0.24 and $V_{in} / SNL = 24dB$.

Because of the more information we can be got from laser beam when the reflection is higher, that means the signal and noise ratio is better, the noise suppression will be better as shown in fig.3. When reflection R is large enough, the increase of noise suppression efficiency become flat. In order to obtain both the output power and noise suppression efficiency simultaneously, we select the reflection $R=0.3$.

With best selecting delay time, bandwidth filter and gain of feedback loop, the noise of suppression vs analysis frequency is shown in fig. 4 when the reflection $R=0.3$. The maximum noise reduction 22dB is obtained at 6MHz, and the noise is near to SNL. The output noise only can be most suppressed at a frequency point with limited bandwidth due

to limitation of bandwidth of optoelectronic feedback loop. In order to suppress noise in large range of frequency, we can use a high finesses cavity as model cleaner to suppress wideband noise effectively. We have obtained the shot noise limit laser from 3MHz by mode cleaner [Liu, K. et al. 2009].
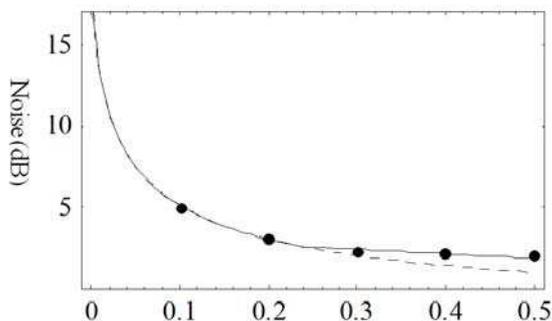

Fig. 3. Residual Noise Vs Reflectivity. ● The results of experiment; --- The results of theory , $\eta_2 = 0.95$; — The results of theory , $\eta_2 \times R = 0.24$.
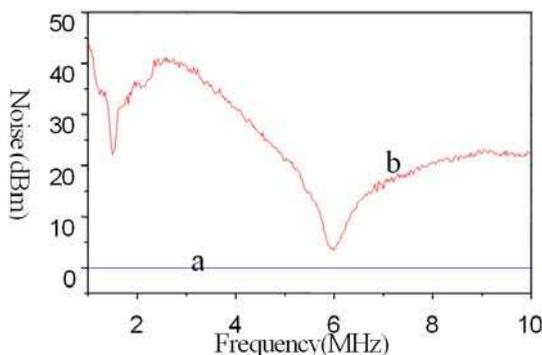

Fig. 4. The best noise suppression of Fiber Laser with Opt-Electronic feedbak at 6.2 MHz . a) the electronics noise. b) the SNL.

3. Generation of sub-poissonian state

Sub-Poissonian light is an important light source in studies of quantum information and optical communication. Sub-Poissonian light is also the light with the largest communication capacity in known light fields (Yamamoto, Y. & Haus, H. 1986). There are three techniques for generation of sub-Poissonian light: direct conversion, a feedback technique, and a feed-forward technique. In 1990 Mertz et al. (Mertz, J. et al. 1990) obtained sub-Poissonian light by using the feed-forward technique and a nondegenerate optical parametric oscillator (NOPO) pumped by the 528 nm line of an argon-ion laser; the observed noise reduction was as much as 24% below the shot-noise limit (SNL).Subsequently, Kim and Kumar (Kim, C. & Kumar, P. 1992) analyzed theoretically the

generation of tunable sub-Poissonian light with an intensity feed-forward scheme for application in precision absorption spectroscopy. Then, pulses sub-Poissonian light was obtained experimentally also by traveling wave optical parametric deamplification (Li, R. et al. 1995). In 2006 Zou, H. obtained noise reduction of 45% wavelength tunable sub-Poissonian light by using the feed-forward technique (Zou, H. et al. 2006).

Zhang *et al.* (Zhang, Y. et al. 2002) presented statistics on twin beams emerging from a nondegenerate OPO. They recorded the twin beams' photocurrent difference fluctuation and demonstrated sub-Poissonian distributions of the twin beams' intensity difference. Laurat et al. (Laurat, J. et al. 2003) reported their experimental demonstration of the conditional preparation of a continuously variable nonclassical state of light from twin beams by a data-acquisition system; this is a kind of postselected sub-Poissonian light.

In this section we demonstrate the achievement of a frequency-tunable high-intensity sub-Poissonian state with optoelectronic feed-forward and quantum-correlated twin beams. A maximum noise reduction of 2.6 dB (45%) below the SNL was measured, and a wavelength tunable range of 7.4 nm was demonstrated. Sub-Poissonian distribution with twin beams was also demonstrated by direct measurement of the sub-Poissonian state.

3.1 The principle of generation sub-Poissonian light by optoelectronics

Generation of quantum-correlated twin beams is a prerequisite to our scheme. It is well known that a NOPO running above threshold is one of the best choices for intensity-correlated twin beams. Several groups of scientists have demonstrated experimentally quantum correlation of the intensity of twin beams. The intensity feed-forward scheme is shown schematically in Fig. 5.
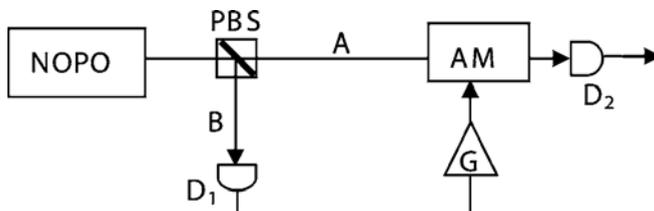

Fig. 5. Schematic of the feed-forward scheme. The quantum-correlated signal and idler beams from the NOPO are separated into beams A and B. Beam B is directly detected by detector D1 to correct beam A by modulation. PBS: polarization beam splitter; G:amplifier; AM: amplitude modulator; NOPO: nondegenerate optical parametric oscillator.

Beams A and B from the NOPO are quantum-correlated twin beams (signal and idler). Beam B is detected directly to correct beam A. After optimum correction, intensity noise S_A^{opt} of beam A at analysis frequency becomes (Mertz, J. et al. 1990)

$$S_A^{opt} = 2S_{A-B}(\Omega)[1 - \frac{S_{A-B}(\Omega)}{2S(\Omega)}] \tag{9}$$

where $S(\Omega)$ is the intensity noise spectrum of a single beam (beam A or beam B) and $S_{A-B}(\Omega)$ is the noise spectrum of the intensity difference between the twin beams, which characterizes the quantum correlation between the twin beams. Both $S(\Omega)$ and $S_{A-B}(\Omega)$ are normalized to their respective SNL. The intensity noise of a single beam is decided mainly

by the OPO's state of operation. While the OPO cavity operates close to oscillator threshold, each beam generated by the OPO in general has a large amount of excess noise. Under the circumstances, the intensity noise spectrum of corrected beam A can be written approximately as

$$S_A^{opt} = 2S_{A-B}(\Omega) \tag{10}$$

It is obvious that only when the intensity difference squeezing is more than 3 dB ($S_{A-B} < 0.5$) can the noise power of the corrected signal beam be below the shot-noise level, that is, sub-Poissonian light.

3.2 Experiment and results

A schematic of the experimental setup is shown in Fig. 6. A homemade intracavity frequency-doubled and frequency-stabilized cw ring neodymium:yttrium aluminum perovskite laser serves as the light source. The output second-harmonic wave at 540 nm is used to pump the semimonolithic NOPO. The oscillation threshold is less than 120 mW, and an output power of 40 mW is obtained at a pump power of 170 mW.

The output infrared beams are reflected by dichroic mirror M and then separated by a polarizing beam splitter (PBS) into detection arms A and B. The detectors (PA$_1$, PA$_2$, PB$_1$, and PB$_2$) are Epitax 500 p-i-n photodiodes, with quantum efficiencies of about 0.94. The displacement operation is performed by use of an electro-optical modulator and a highly reflecting (99/1) mirror with the help of a local beam for reducing loss.
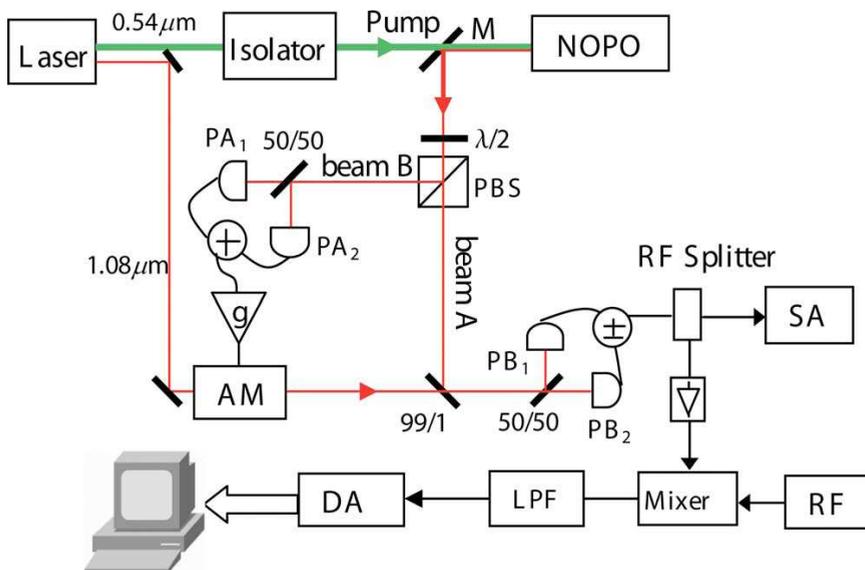

Fig. 6. (Color online) Experimental setup: PA$_i$, PB$_i$ (i=1,2): photodetectors; AM: amplitude modulator; RF Splitter: radio-frequency power splitter; SA: spectrum analyzer; RF: radio-frequency signal; LPF: low-pass filter; DA: data acquisition card; PBS: polarization beam splitter; M: mirror.
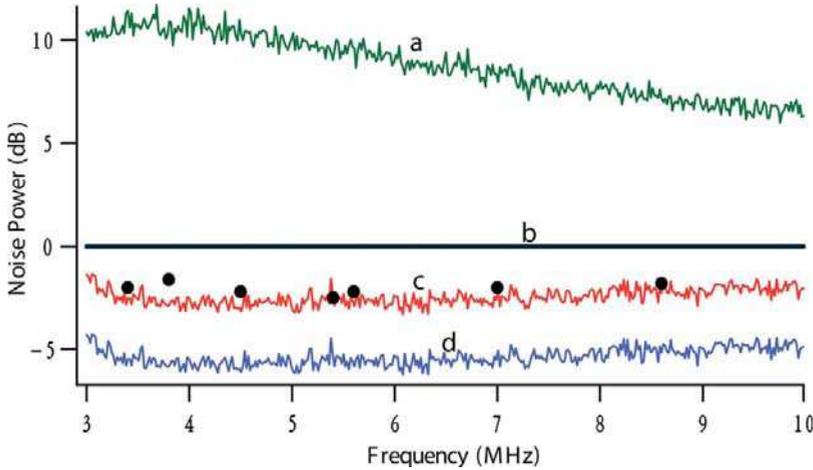
Fig. 7. (Color online) Noise spectra from 3 to 10 MHz. All noise power is normalized to the corresponding SNL. Curve *a*, noise without feed-forward correction; curve *b*, the SNL. Curve *d*, noise spectrum of the intensity difference between the signal and the idler fields. Curve *c*, obtainable noise of beam A [according to Eq. (9)] with data curve *a* and curve *d*. Filled circles, experimentally measured results.

Experimental results are shown in Fig. 7. All the noise power spectra are normalized to their respective SNL. Curve a is the noise power spectrum of beam A without feed-forward correction $S(\Omega)$; line b is the normalized SNL. It is clear that the single beam has a large mount of excess noise. The excess noise is typically 6–10 dB above the SNL in the measurement 3–10 MHz. Curve d is the noise power spectrum of the intensity difference between the twin beams $S_{A-B}(\Omega)$, the quantum correlation between beams A and B. The curve exhibits a more than 5 dB intensity difference squeezing in the entire range, and the maximum value reaches 5.7 dB near 4.5 MHz. Curve c is the obtainable minimum noise power of the sub-Poissonian beam (corrected beam A) according to Eq. (9) with data curve a $S(\Omega)$ and curve d $S_{A-B}(\Omega)$. Because there is much excess noise in each beam from the OPO, curve c is approximately 3 dB higher than curve d [Eq. (10)]. The filled circles in Fig. 7 are the directly measured noise power of prepared sub-Poissonian light at different analysis frequencies. It is clear that the maximum noise reduction is 2.6 dB (45%) below shot-noise level at 5.5 MHz frequency, and the experimental result accords well with the expected values of curve c.

We tuned the sub-Poissonian wavelength roughly by changing the KTP crystal temperature in the OPO. A wavelength range from 1078.9 to 1083.8 nm is covered for a signal beam, and the noise of a sub-Poissonian field is reduced to more than 2 dB below the SNL throughout all the wavelength-tunable range, as shown in Fig. 8. If arm A is measured to control arm B, a range from 1076.4 to 1081.2 nm for the sub-Poissonian field will be demonstrated. One can also obtain continuous frequency tuning by tuning the laser frequency

Additionally, the distribution of sub-Poissonian light is acquired as shown in Fig. 9. In the experimental setup (Fig. 6), a part of the signal after rf splitting is mixed with a sinusoidal local oscillator at 5.5 MHz. After a 100 kHz low-pass filter, the signal is collected at a sampling rate of 500 kHz by a 12 bit acquisition card. The statistical distribution of the

photocurrent fluctuation is shown in Fig. 9, with 200,000 points for each curve. The points in the figure are the experimental results, and the solid curves are Gaussian fits of the probability distribution. Curve a represents the probability distribution of the prepared sub-Poissonian field, curve b corresponds to a coherent state (the SNL), and curve c corresponds to single-beam field without correction. It is shown that the sub-Poissonian distribution of light fluctuation is narrower than a standard Gaussian distribution of the coherent state. The uncorrected single-beam fluctuation distribution is a super-Poissonian and is much broader than the standard Gaussian distribution. The photocurrent fluctuation of the sub-Poissonian field can also be compared with the standard Gaussian distribution. A noise reduction of 1.2 dB below the SNL is calculated from average half-widths (Fig. 9) and does not accord well with what we observed with the spectrum analyzer because of the narrow bandwidth of the prepared sub-Poissonian field and a nonideal low-pass filter. The calculated photocurrent fluctuation of a single beam is 9 dB above the SNL, which accords well with what we observed with the spectrum analyzer.
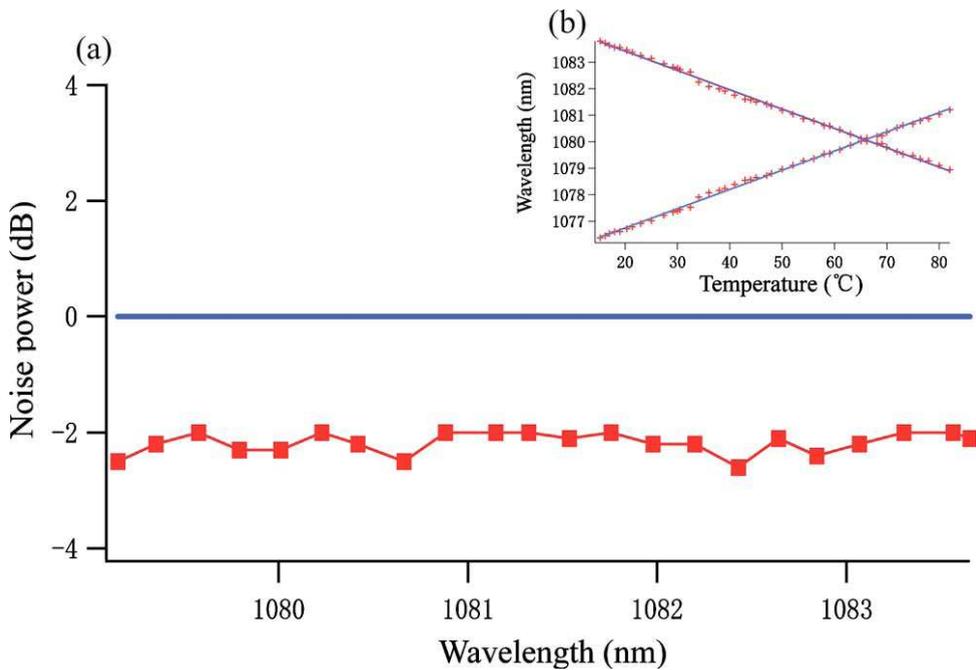

Fig. 8. (Color online) (a) Normalized sub-Poissonian light noise from 1079 to 1083.7 nm. (b) Wavelength of twin beams versus temperature of the crystal in the OPO.
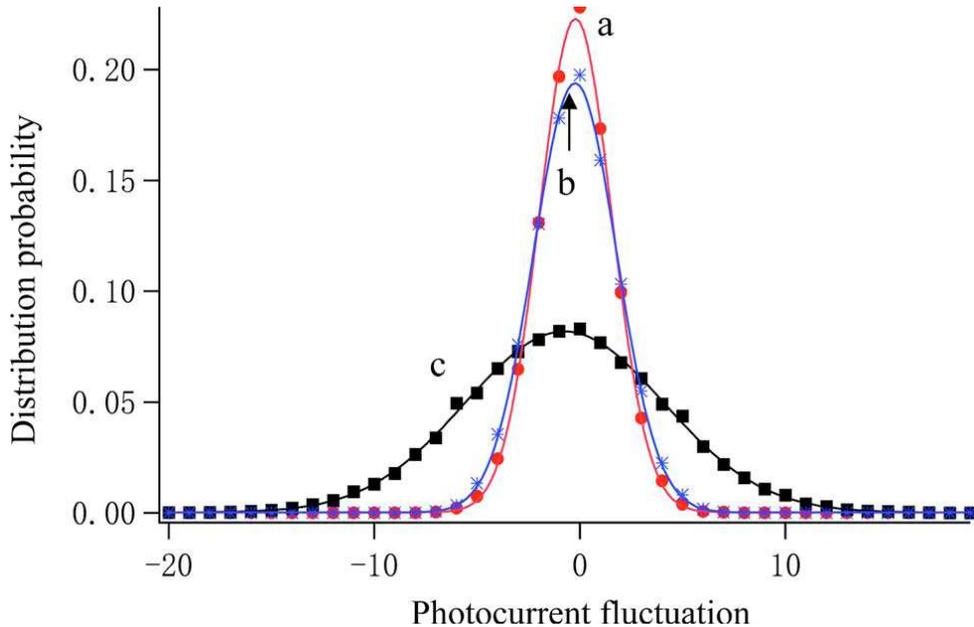
Fig. 9. (Color online) Intensity fluctuation distribution at 5.5 MHz. Curve *a*, prepared sub-Poissonian field; curve *b*, coherent light; curve *c*, single beam from the NOPO (beam A).

4. Conclusion

We introduce the application of opto-electronics feed-forward in noise suppression, including both classical noise (fiber laser noise suppression) and quantum noise (preparing sub-Poissonian) suppression. The technique of opto-electronics has been widely applied and will be more and more significant in the field of quantum optics and quantum information.

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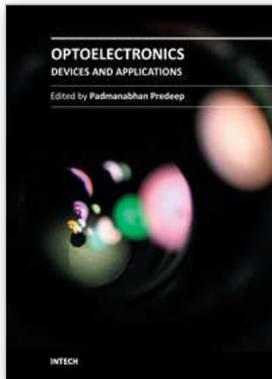
Optoelectronics - Devices and Applications

Edited by Prof. P. Predeep

Optoelectronics - Devices and Applications is the second part of an edited anthology on the multifaced areas of optoelectronics by a selected group of authors including promising novices to experts in the field. Photonics and optoelectronics are making an impact multiple times as the semiconductor revolution made on the quality of our life. In telecommunication, entertainment devices, computational techniques, clean energy harvesting, medical instrumentation, materials and device characterization and scores of other areas of R&D the science of optics and electronics get coupled by fine technology advances to make incredibly large strides. The technology of light has advanced to a stage where disciplines sans boundaries are finding it indispensable. New design concepts are fast emerging and being tested and applications developed in an unimaginable pace and speed. The wide spectrum of topics related to optoelectronics and photonics presented here is sure to make this collection of essays extremely useful to students and other stake holders in the field such as researchers and device designers.

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