Influence of birefringence induced at low temperature on balanced detection of polarization-dependent photon-number squeezing and its optical compensation

Jing Zhang, Tiancai Zhang, Ruifang Dong, Junxiang Zhang, Junmin Wang, Changde Xie, and Kunchi Peng

Key Laboratory of Quantum Optics, Ministry of Education, China, and Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China

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The polarization-dependent photon-number squeezing of 1.5 dB from a grating feedback locking quantum-well laser in a cryostat has been experimentally detected with a balanced homodyne detector including an imperfect nonpolarized-beam splitter. The great influence of the birefringence induced at low temperature on the determination of the shot-noise-limit and on the detection of photon-number squeezing is discussed in detail. Birefringence is compensated for by insertion of a half-wave plate of adjustable inclination into the output beam before the polarization components of the optical system.
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1. INTRODUCTION

The generation of photon-number squeezed states from laser diodes (LDs) has been extensively studied for its potential applications in precise measurements and quantum information processing. In particular, injection-locked LD systems[1–4] have attracted wide attention in scientific and technical fields because they can provide convenient tunable nonclassic light sources for quantum-optical spectroscopy.[5–7] The variety and dependence of experimental results on the devices and optical configurations encouraged us to study further the physical mechanism that influences the squeezing detection of a laser diode. A group of researchers at the Randall laboratory, University of Michigan, discussed the polarization dependence of LD intensity noise and the induced birefringence effect at low-temperatures[2]; later they suppressed these effects, using polarization-preserving balanced homodyne detection, and demonstrated photon-number fluctuation 4.5 dB below the shot-noise limit (SNL) at 15 K with a quantum-well laser that was injection locked by a tunable dye laser.[8] An elegant explanation of the phenomenon of the increase in noise when a polarizer is introduced was suggested in Ref. 8, where the inherent anticorrelation and the anticorrelation induced by birefringence between orthogonally polarized fields were designated the main reasons. But, in our experiment, we found that the influence of the inherent anticorrelation fluctuation from the orthogonally polarized component of laser on detection of the noise spectrum is not significant, because the fluctuation noise is 10 dB lower less than that of the main polarization output; however, the effect of induced birefringence in the laser and the optics at low-temperature is most important.

Although perfect polarization-preserving balanced homodyne detection, which requires that no polarizer be inserted before balanced detection and that a 50% beam splitter for balanced detection be perfectly nonpolarizing, can give the correct photon-number squeezing and the SNL level by means of standard balanced detection, perfect polarization preservation is not always achieved: for instance, when a polarizer is inserted before balanced detection or when the beam splitter used in a homodyne detector has a few polarizations. For imperfect polarization-preserving balanced homodyne detection, the SNL level measured with the standard balanced detection technique and the squeezed noise spectrum are incorrect. By inserting a half-wave plate of adjustable inclination into the output beam to compensate for the birefringence, and a polarizer behind the $\lambda/2$ plate, we determine a SNL that is in good agreement with that obtained by calibration with a filtered white-light source and detect 1.5-dB photon-number squeezing of the output laser from a grating feedback locked quantum-well laser at 80 K in a cryostat.[6] Our experiments show that the polarization-dependent photon-number squeezing from a laser system in a cryostat can be precisely detected by an imperfect polarization-preserving balanced homodyne detector and that the polarization components can be placed in the optical configuration before detection so long as a simple birefringence compensator is used.

2. EXPERIMENTAL SETUP AND RESULT

The experimental setup for generating photon-number squeezed states of light from a semiconductor diode laser is shown in Fig. 1. The quantum-well laser diode (Spectra Diode Laboratories 5411-G1) and the collimation lens were cooled to 80 K inside a liquid-nitrogen cryostat to in-

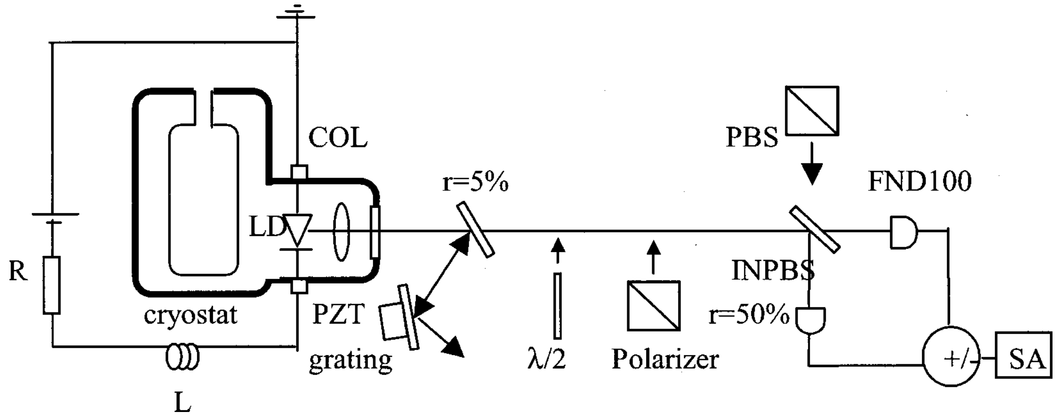

Fig. 1. Experimental setup for generation of amplitude-squeezed states of light from a diode laser: COL, collimater; PZT, piezoelectric transducer controlling the grating; INPBS, imperfect nonpolarizing beam splitter; PBS, polarizing beam splitter; SA, spectrum analyzer; R, resistance; L, inductance; r, reflection coefficient.

crease the electron-to-photon conversion efficiency. Because of the presence of multiple subthreshold longitudinal side modes in the laser diode, line-narrowing techniques have to be used to produce amplitude squeezing. In as much as phase noise of the laser diode is highly sensitive to wavelength-selected optical feedback, weak optical feedback is enough to effectively suppress the longitudinal side modes. The quantum-well laser output is oriented such that the polarization component parallel to the laser junction has a strong output. The weak perpendicularly polarized component experiences large cavity loss close to threshold. The weak-polarization component has intensity noise far above the SNL because of the absence of strong gain saturation, and the characteristic is similar to that for the longitudinal side modes. In our experiment we used a high-transmission beam splitter with a transmission of 95% to reflect a small portion of the laser beam onto a grating (1200 lines/mm). The first-order diffracted beam was reflected and fed back to the laser diode by the piezoelectric transducer-controlled grating. At 80 K the threshold current for the laser diode is 2.8 mA. The output beam was detected with two photodiodes (FND100). A 50% beam splitter of imperfect nonpolarization (~6% polarization dependence) and one of perfect polarization (100% polarization dependence), respectively, were used to divide the squeezed light into two detectors (balanced homodyne detection configuration). The overall detection efficiency including optical losses and detector efficiency was near 84%. The sum or difference of photocurrent noises was measured with a spectrum analyzer. The SNL was confirmed by a red-filtered white-light source with the same dc photocurrent.

The amplitude noise spectra from the laser output without polarization analysis are shown in Fig. 2. The laser diode is biased at 30.6 mA, giving a corresponding photodetector dc current of 12.2 mA. The efficiency of conversion of injection current into detector current is 40%, from which the estimated squeezing is ~2.2 dB. Figure 2A shows the measured noise spectra with the imperfect nonpolarizing beam splitter of the balanced homodyne detection, which has little dependence on polarization. We measure the maximum and minimum transmission powers $I_T^{\max}$ and $I_T^{\min}$ by rotating the polar-

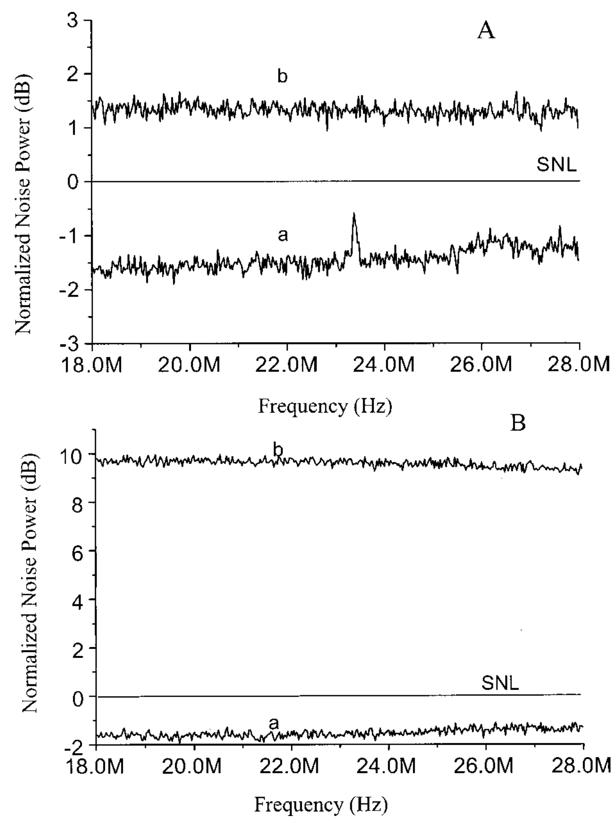

Fig. 2. A, Measured noise spectra with the nonideal nonpolarizing beam splitter for balanced homodyne detection. B, measured noise spectra with the polarizing beam splitter for balanced homodyne detection.

ization of input light and calculate the polarization dependence $(I_T^{\max} - I_T^{\min})/(I_T^{\max} + I_T^{\min}) = 6\%$. Trace a is the sum of photocurrents of the laser output noise 1.6 dB below the SNL. Trace b is the difference of photocurrents that gives the incorrect SNL. Figure 2B shows the measured noise spectra with the balanced homodyne detection for the same conditions but with the beam splitter 100% polarizing; the sum photocurrent (trace a) overlaps trace a of Fig. 2A. Trace b is the difference of photocurrents, which is far above trace b of Fig. 2A. For the perfect nonpolarizing beam splitter the two orthogonally polarized components of laser output couple only the same polarized vacuum noise injected from the dark port; therefore the difference of photocurrents is the strong coherent component of laser field beating with the vacuum noise that gives true SNL at the same dc photocurrent. When an imperfect nonpolarization beam splitter is used, the vacuum noise from the dark port and the large noise of the perpendicular-polarization component from the bright port will be coupled in the parallel laser component. So the difference of photocurrents of Fig. 2A gives a false SNL that is 1.6 dB greater than the real SNL. When the polarization beam splitter is used, the polarization of the input light is 45° with respect to the polarizer, so the parallel-polarization component couples only the perpendicular-polarization component that comes from the bright port. The parallel-polarization component that has large magnitude is just as likely to serve as the local beam in a normal homodyning detector to measure the noise of the weak perpendicular-polarization component.[9] The difference of currents in Fig. 2B gives the noise of a weak perpendicularly polarized field, which is 9.8 dB above the SNL.

The polarization-extinction ratio for the laser output at room temperature is better than 100:1, but at the low temperature of 80 K, when a linear polarizer is introduced and aligned for maximum transmission, which corresponds to the polarization axis parallel to the laser junction, the measured polarization-extinction ratio is reduced to 10:1. The relatively small polarization-extinction ratio for the laser output from the cryostat is due primarily to the birefringence of the collimating lens and the LD induced at low temperature, which results in elliptically polarized output. When a polarizer is introduced, the projections of the orthogonal field components onto the polarizer axis will interfere; therefore the squeezing level of the main polarization component after mixing the large noisy component must be decreased. Trace a of Fig. 3 gives the measured noise of the laser field 2.3 dB above the SNL. Through the polarizer, the perpendicularly polarized component is changed into vacuum noise, and the difference of currents will give the correct SNL, no matter whether a nonpolarizing or a polarizing beam splitter is used. To eliminate the effect of birefringence, we place a half-wave silicon plate of 1.6-mm thickness before the linear polarizer and adjust its angle of inclination to make the maximum transmission through the linear polarizer, in this case the difference of optical distances between two orthogonal polarizations that results when the laser and optics at low temperature are compensated for. A polarization-extinction ratio of >100:1 is recovered. Then 1.5-dB squeezing is observed again, which is close to the result measured by polarization-preserving balanced homodyne detection (without a linear polarizer), as shown in trace b of Fig. 3.

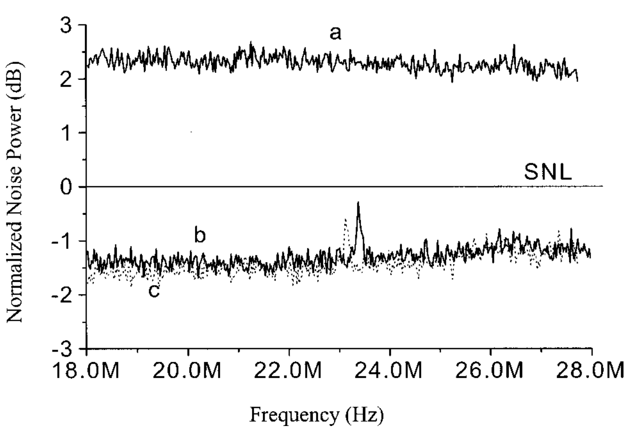

Fig. 3. Measured noise spectra with a linear polarizer. Trace a, the power spectrum of the laser output degraded owing to the effect of birefringence. Trace b, power spectrum retrieved by phase compensation. Trace c, power spectrum obtained from polarization-preserving balanced homodyne detection.

3. THEORETICAL ANALYSIS

Figure 4 is a diagram of balanced homodyne detection with the polarization-dependent beam splitter for a theoretical explanation of the experiments. $a_\parallel^{\text{in}}$ and $a_\perp^{\text{in}}$ are annihilation operators for parallel- and perpendicularly polarized laser output fields, respectively ($\langle a_\parallel^{\text{in}}\rangle \gg \langle a_\perp^{\text{in}}\rangle \approx 0$). $a_\parallel^v$ and $a_\perp^v$ are annihilation operators for vacuum fields from the dark port of a beam splitter ($\langle a_\parallel^v\rangle = \langle a_\perp^v\rangle = 0$). The polarization of a laser output field must be rotated 45° by a half-wave plate at 22.5° for balanced homodyne detection. The output beam's annihilation operators from a half-wave plate are expressed as follows:

$$a_\parallel^{hw} = \frac{\sqrt{2}}{2}(a_\parallel^{\text{in}} + a_\perp^{\text{in}}), \qquad a_\perp^{hw} = \frac{\sqrt{2}}{2}(a_\parallel^{\text{in}} - a_\perp^{\text{in}}). \quad (1)$$

The reflection coefficient and transmission of a polarization-dependent beam splitter for the parallel and perpendicular directions are $R_\parallel$, $T_\parallel$ ($R_\parallel + T_\parallel = 1$) and $R_\perp$, $T_\perp$ ($R_\perp + T_\perp = 1$), respectively. We can assume that $R_\parallel = T_\perp = R$ and $R_\perp = T_\parallel = T$ for a general polarization-dependent beam splitter. The dependence on polarization for a beam splitter can be evaluated with $|T - R|$. Hence the output light fields from the polarization-dependent beam splitter can be expressed in terms of the input beams:

$$\begin{aligned} c_\parallel &= \frac{\sqrt{2}}{2}\sqrt{T_\parallel}(a_\parallel^{\text{in}} + a_\perp^{\text{in}}) + \sqrt{R_\parallel a_\parallel^v}, \\ c_\perp &= \frac{\sqrt{2}}{2}\sqrt{T_\perp}(a_\parallel^{\text{in}} - a_\perp^{\text{in}}) + \sqrt{R_\perp}a_\perp^v, \\ d_\parallel &= \frac{\sqrt{2}}{2}\sqrt{R_\parallel}(a_\parallel^{\text{in}} + a_\perp^{\text{in}}) - \sqrt{T_\parallel a_\parallel^v}, \\ d_\perp &= \frac{\sqrt{2}}{2}\sqrt{R_\perp}(a_\parallel^{\text{in}} - a_\perp^{\text{in}}) - \sqrt{T_\perp}a_\perp^v. \end{aligned} \quad (2)$$

The average photocurrent incident upon detectors D_1 and D_2 is

$$\bar{I} = \langle i_1\rangle = \langle i_2\rangle = 1/2\zeta\langle a_\parallel^{\text{in}+}a_\parallel^{\text{in}}\rangle, \quad (3)$$

where ζ is the detection efficiency ($0 \leqslant \zeta \leqslant 1$). Here we have assumed that the polarization-dependent beam splitter is a 50% beam splitter and that two arms of a homodyning detector have the same dc photocurrent. The photocurrent of the each arm of the balanced homodyne detection consists of two parts; one is the self-terms of the

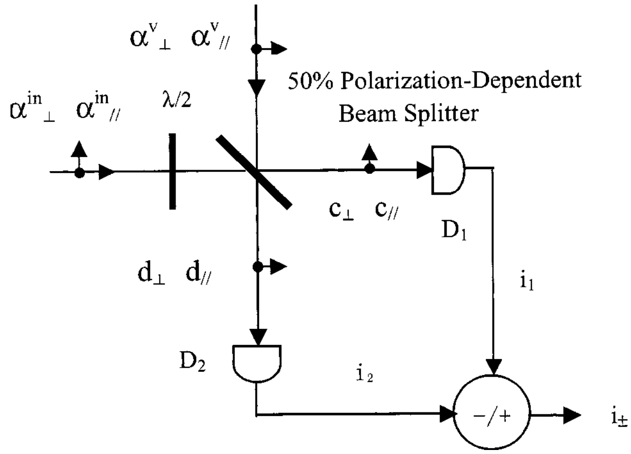

Fig. 4. Balanced homodyne detection with the polarization-dependent beam splitter.

input modes at the port of beam splitter, and the other is the interference terms. The self-terms of two arms are correlated (or in phase), and the interference terms are anticorrelated (or out of phase). Thus the sum of photocurrents of two arms retains only the self-terms and the difference photocurrent retains the interference terms. The noise of the sum of the photocurrents is now given as

$$\langle(\delta i_+)^2\rangle = 2\bar{I}\langle(\Delta X_\parallel^{\text{in}})^2\rangle, \tag{4}$$

where $\langle(\Delta X_\parallel^{\text{in}})^2\rangle$ is the fluctuation of the quadrature amplitude of parallel-polarized laser output field. To get the sum of photocurrents, an alternative method is to use a single photodiode to measure the noise of the output laser beam directly. The same sum photocurrent noise spectra of 1.6 dB below the SNL have been obtained, which were not dependent on the polarization property of the beam splitter as shown by traces a of Figs. 2A and 2B. The noise of the difference of photocurrents is given as

$$\begin{aligned}\langle(\delta i_-)^2\rangle &= 2\bar{I}\{(R - T)^2\langle(\Delta X_\perp^{\text{in}})^2\rangle + 1/2[1 - (R - T)^2] \\ &\quad \times \langle(\Delta X_{a_\parallel^v})^2\rangle + 1/2[1 - (R - T)^2]\langle(\Delta X_{a_\perp^v})^2\rangle\}, \\ &= 2\bar{I}[(R - T)^2\langle(\Delta X_\perp^{\text{in}})^2\rangle + 4RT)], \end{aligned} \tag{5}$$

where $\langle(\Delta X_\perp^{\text{in}})^2\rangle$ is the fluctuation of the quadrature amplitude of a perpendicularly polarized laser output field and $\langle(\Delta X_{a_\parallel^v})^2\rangle$ and $\langle(\Delta X_{a_\perp^v})^2\rangle$ are the fluctuations of the vacuum input field from the dark port $(\langle(\Delta X_{a_\parallel^v})^2\rangle = \langle(\Delta X_{a_\perp^v})^2\rangle = 1)$. From the measured polarization dependence of the beam splitter used in our experiments we can calculate the noise of the difference of photocurrents, that is, 1.3 dB above the SNL, in good agreement with trace b of Fig. 2A. For the ideal nonpolarizing beam splitter ($R = T = 50\%$), the noise of the difference of photocurrents is changed into

$$\langle(\delta i_-)^2\rangle = 2\bar{I}[1/2\langle(\Delta X_{a_\parallel^v})^2\rangle + 1/2\langle(\Delta X_{a_\perp^v})^2\rangle] = 2\bar{I}. \tag{6}$$

Equation (6) illustrates that the difference of photocurrents of a perfectly nonpolarizing beam splitter gives the true SNL. For the polarizing beam splitter ($R = 1$, $T = 0$), the noise of the difference of photocurrents is

$$\langle(\delta i_-)^2\rangle = 2\bar{I}\langle(\Delta X_\perp^{\text{in}})^2\rangle. \tag{7}$$

The noise of the quadrature amplitude of a perpendicularly polarized laser output field measured with the polarizing beam splitter is shown as trace b of Fig. 2B. When a polarizer is introduced before balanced detection, the projections of the orthogonal field components onto the polarizer axis will interfere: $a_\parallel^{\text{in}} = \sqrt{1 - \xi_{bf}}a_\parallel^{\text{LD}} + \sqrt{\xi_{bf}}a_\perp^{\text{LD}}$, where ξ_{bf} is a birefringence coupling coefficient, which is approximately equal to the difference of polarization extinction ratios (1/10 − 1/100). The squeezing level of the main polarization component mixed with the large noisy component will be degraded. Trace a of Fig. 3 gives the measured noise of the laser field as 2.3 dB above the SNL. Through the polarizer, the perpendicularly polarized component is transformed into vacuum noise $[\langle(\Delta X_\perp^{\text{in}})^2\rangle = 1]$, and the difference of currents from Eq. (5) will give the correct SNL whether a nonpolarizing or a polarizing beam splitter is used.

Emission along the two polarization axes that couple to the same upper-state population and experience quantum-correlated amplitude fluctuations in much the same manner that quantum correlations arise among different longitudinal modes was considered in Ref. 7. But the noise power of the perpendicularly polarized component should be less than 10 dB of the main polarization component because the average photon number of the former is 20 dB less than that of the latter, although the amplitude variance $\langle(\Delta X_\perp)^2\rangle$ is 10 dB above the SNL. So the perpendicularly polarized component holds only a small amount of quantum information about the photon number in the squeezed parallel-polarized field and has almost no influence to the noise spectrum of the output field, as shown in traces b and c of Fig. 3.

4. CONCLUSION

In conclusion, we have found that the key influence on photon-number squeezing measured by a balanced homodyning detector comes from the birefringence at low temperature. Once the birefringence effect is compensated for by insertion of a half-wave plate of adjustable inclination and a polarizer, the correct SNL level and photon-number squeezing can be detected even with an imperfect nonpolarization balanced detector. The advantages of our scheme are that the influence of polarization of the 50% beam splitter used in the balanced detection to the noise measurement is avoided and that any polarization components can be inserted into the optical configuration between the half-wave plate and the balanced homodyning detector.

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Jing Zhang's e-mail address is jzhang74@yahoo.com.

REFERENCES

1. S. Inoue, S. Machida, Y. Yamamoto, and H. Ohzu, "Squeezing in an injection-locked semiconductor laser," Phys. Rev. A **48**, 2230–2234 (1993).
2. H. Wang, M. J. Freeman, and D. G. Steel, "Squeezing light from injection-locked quantum well lasers," Phys. Rev. Lett. **71**, 3951–3954 (1993).
3. A. Furusawa, "Amplitude squeezing of a semiconductor laser with light injection," Opt. Lett. **21**, 2014–2016 (1996).
4. T.-C. Zhang, J.-Ph. Poizat, P. Grelu, J.-F. Roch, P. Grangier, F. Marin, A. Bramati, V. Jost, M. D. Levenson, and E. Giacobino, "Quantum noise of free-running and externally-stabilized laser diode," Quantum Semiclassic. Opt. **7**, 601–613 (1995).
5. S. Kasapi, S. Lathi, and Y. Yamamoto, "Amplitude-squeezed, frequency-modulated, tunable, diode-laser-based source for sub-shot-noise FM spectroscopy," Opt. Lett. **22**, 478–480 (1997).
6. Y.-Q. Li, P. Lynam, M. Xiao, and P. Edward, "Sub-shot-noise laser Doppler anemometry with amplitude-squeezed light," Phys. Rev. Lett. **78**, 3105–3108 (1997).
7. Y.-Q. Li and M. Xiao, "Generation and applications of amplitude-squeezed states of light from semiconductor diode lasers," Opt. Express **2**, 110–117 (1998), http://www.opticsexpress.org.
8. D. C. Kilper, D. G. Steel, R. Craig, and D. R. Scifres, "Polarization-dependent noise in photon-number squeezed light generated by quantum-well lasers," Opt. Lett. **21**, 1283–1285 (1996).
9. P. Grangier, R. E. Slusher, B. Yurke, and A. LaPorta, "Squeezed-light-enhanced polarization interferometer," Phys. Rev. Lett. **59**, 2153–2156 (1987).