Ultrasensitive pulsed, balanced homodyne detector: application to time-domain quantum measurements

H. Hansen, T. Aichele, C. Hettich, P. Lodahl, A. I. Lvovsky, J. Mlynek, and S. Schiller*

Fachbereich Physik, Universität Konstanz, M696, D-78457 Konstanz, Germany

Received April 24, 2001

A pulsed, balanced homodyne detector has been developed for precise measurement of the electric field quadratures of pulsed optical quantum states. A high level of common mode suppression (>85 dB) and low electronic noise (730 electrons per pulse) provide a signal-to-noise ratio of 14 dB for measurement of the quantum noise of individual pulses. Measurements at repetition rates as high as 1 MHz are possible. As a test, quantum tomography of the coherent state was performed, and the Wigner function and the density matrix were reconstructed with 99.5% fidelity. The detection system can be used for ultrarsensitive balanced detection in cw mode, e.g., for weak absorption measurements. © 2001 Optical Society of America

OCIS codes: 270.5570, 270.5290.

The rapidly developing field of quantum information technology requires reliable means of characterizing optical quantum states. In application to nonclassical light, balanced homodyne detection (BHD) has proved invaluable for the direct measurement of electric field quadratures of electromagnetic modes. BHD, which was proposed in 1983 by Yuen and Chan,[1] was initially used to detect squeezed states of the electromagnetic field[2,3] and later for such fundamental experiments as complete characterization of quantum states by means of quantum tomography,[4–6] establishing Einstein–Podolsky–Rosen-type quantum correlations[7] and continually variable quantum teleportation.[8] Recently, BHD was employed to demonstrate nonclassical properties of electromagnetic fields in cavity QED.[9] BHD is expected to play a major role in quantum information processing in the future.

To date, most BHD measurements have been performed in the frequency domain. A significant drawback of this approach is that it reveals information about the quantum state only within the sideband chosen for the measurement. Therefore the method is incompatible with other techniques (e.g., photon counting) for characterizing a quantum state for which such precise selection of spectral modes is impossible.

Time-domain BHD resolves this limitation. It was employed by Raymer and colleagues in their pioneering experiments on quantum tomography and quantum correlations.[4,10,11] Their homodyne detector could resolve shot (vacuum) noise of individual pulses with a signal-to-noise ratio of 6 dB at a subkilohertz repetition rate. The restrictions arose from the electronic subtraction efficiency [local oscillator (LO) powers limited to 4×10^6 photons per pulse], electronic detection noise (580 electrons per pulse), and slow amplification electronics.

In this Letter, we present a time-domain BHD system whose characteristics substantially surpass those outlined above. We have achieved a signal-to-noise ratio of 14 dB at a pulse repetition rate of as much as 1 MHz, enabling high-accuracy quantum measurements to be carried out in a short time. The detector exhibits 91% quantum efficiency (compared with 85% for the results of Raymer *et al.*).

To perform BHD, one overlaps on a beam splitter the electromagnetic wave whose quantum state is to be measured and a relatively strong LO wave in the matching optical mode. The two fields emerging from the beam splitter are incident upon two high-efficiency photodiodes whose output photocurrents are subtracted. The photocurrent difference is proportional to the value of the electric field operator $\hat{E}_\theta$ in the signal mode, where θ is the relative optical phase of the signal and the LO.

In traditional, frequency-domain BHD one uses a certain frequency component of the difference signal to determine the quadrature quantum noise of the optical state. The measurement frequency is normally chosen to be approximately 5–10 MHz, where the technical noise is minimized. Frequency-domain BHD has been successfully applied in both continuous-wave[1–3,5,12,13] and pulsed[14,15] regimes with a typical signal-to-noise ratio of 20 dB. Squeezed optical states with a quantum noise reduction of as much as 7 dB were measured.[12,13] When applied to pulsed sources, the frequency-domain BHD technique implies that averaging over many individual laser pulses takes place.

In time-domain BHD, however, each laser pulse generates a signal that is observed in real time and yields a single value of a field quadrature. Repeated measurements of a large number of laser pulses produce a quantum probability distribution associated with this quadrature. When transform-limited LO pulses are used, time-domain BHD yields the complete information about the quantum state in the spatiotemporal optical mode that matchs that of the local oscillator. Time-domain BHD is, however, more technically challenging than its frequency-domain counterpart. First, the electronics must ensure time resolution of individual laser pulses. Second, the measured quadrature values must not be influenced by low-frequency noises. The detector must thus provide ultralow noise, high subtraction, and a flat amplification profile in the entire frequency range from dc to at least the LO pulse repetition rate.

An electro-optic schematic of our detector is shown in Fig. 1. We used 1.6-ps, 790-nm pulses from a

0146-9592/01/211714-03$15.00/0

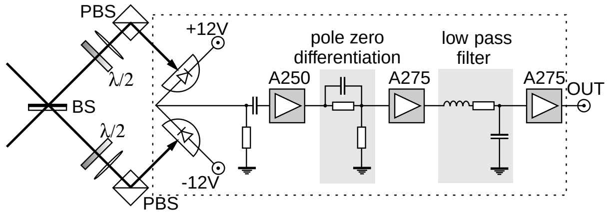

Fig. 1. Electro-optic scheme of the homodyne system.

Spectra-Physics Tsunami laser as the local oscillator. The laser was employed in combination with a pulse picker, which reduced the repetition rate to 200–800 kHz. The orientation of the beam splitter (BS) deviated slightly from 45° to provide a splitting ratio of exactly 50%. The two beam-splitter outputs passed through a pair of $\lambda/2$ plates and polarizing beam-splitter (PBS) cubes, which in combination served as variable attenuators to compensate for the slightly different quantum efficiencies of the photodiodes. The two beams were then focused on a pair of Hamamatsu S3883 Si p–i–n photodiodes of 300-MHz bandwidth and 94% quantum efficiency, which were chosen because of their low-noise equivalent power of 6.7×10^{-15} W Hz$^{-1/2}$. The polarizing beam-splitter cubes, lenses, and $\lambda/2$ plates were antireflection coated for 790 nm, so the total optical losses did not exceed 4%.

The positive and negative charges produced by the optical pulses were collected and physically subtracted at a 470-pF capacitance, which was much larger than the capacitance of the photodiodes (6 pF). The difference charge was then preamplified with a 2SK152 field-effect transistor in connection with a low-noise Amptek A250 preamplifier and further amplified with a five-pole pulse shaping amplifier based on two low-noise Amptek A275 amplifiers. The entire detector electronics, including the photodiodes, was built on a single PC board inside a metal box with dimensions of 2.5 cm × 5 cm × 10 cm. The two photodiodes were mounted at a distance of only 1 cm from each other to minimize spurious rf interferences.

Figure 2(a) shows typical time traces of the homodyne detector difference signal for vacuum signal input. The width of a single electrical pulse is less than 1 μs. Its peak value is a single measurement of the electric field quadrature of the signal wave. The (quantum) noise of the optical pulses indicates the statistical distribution of the quadratures of the vacuum field.

To prove that the pulsed noise shown in Fig. 2(a) is indeed shot noise, we performed a number of tests to make sure that (a) the output rms noise scales as the square root of the LO power, (b) the noise observed away from multiples of the repetition rate is frequency independent (white), and (c) the observed noise power coincides well with the expected magnitude.

Figure 2(b) shows the standard deviation of the pulsed noise as a function of the LO power. After subtraction of the noise background that corresponds to 730 electrons/pulse, the standard deviation of the noise scales with the square root of the LO power, as predicted for the shot noise. Such behavior was observed for LO powers spanning more than 2 orders of magnitude, up to 3×10^8 photons per pulse. This spanning range corresponds to a subtraction efficiency of at least 85 dB. The frequency spectrum of the detector output is shown in Fig. 2(c) and is to a very good approximation white.

We verified the detector amplifier gain and linearity by connecting a 1-pF capacitor to the preamplifier input and inserting small controlled amounts of charges by applying voltage steps of a known size to the capacitor. The detector electronics exhibited excellent linearity within the required dynamic range. The amplifier gain amounted to 2.8 μV per photoelectron; the voltage value refers to the peak of the electronic signal. The measured gain value corresponded to the measured shot-noise magnitude to within the precision of the charge insertion capacitor.

As an application of our BHD system we performed quantum tomography of a coherent state and reconstructed its Wigner function and density matrix. To this end we used pulses from the source laser, which were mode matched with the LO and attenuated almost to the single-photon level. We employed a piezo-mounted mirror in the seed beam's path to scan the relative phase θ between the seed and the LO beams.

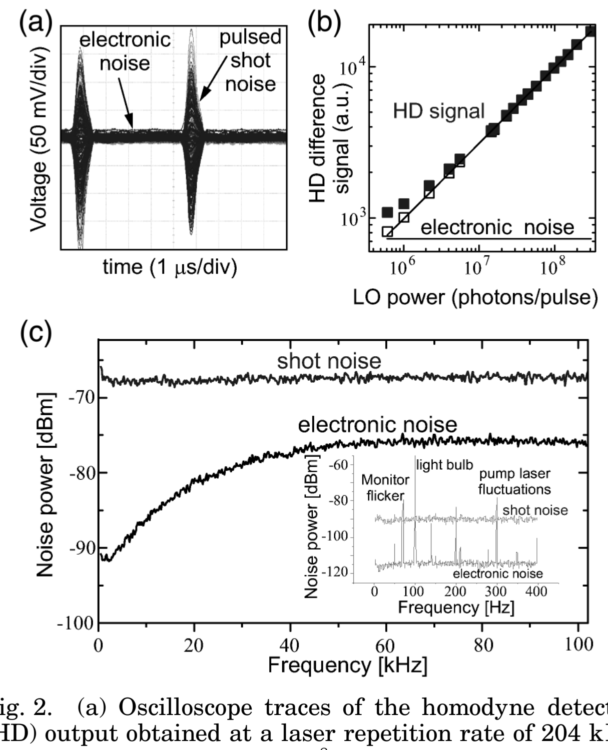

Fig. 2. (a) Oscilloscope traces of the homodyne detector (HD) output obtained at a laser repetition rate of 204 kHz and a LO power of 1.6×10^8 photons per pulse. Each laser pulse produces a time-resolved quantum noise sample. (b) rms peak amplitude of the noise pulses as a function of the LO power, showing the expected square root power dependence on the LO intensities of 3×10^8 photons per pulse. The filled squares show the measured noise variances; the open squares were obtained from these values by subtraction of the noise background. (c) Frequency-resolved noises at a LO power of 2.3×10^7 photons per pulse. Inset, the low-frequency spectrum illustrates the strong effect of background light sources.

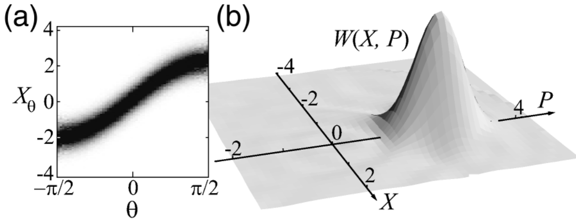

Fig. 3. (a) Raw quadrature data and (b) reconstructed Wigner function of a coherent state with the excitation $\alpha = 2.24$.

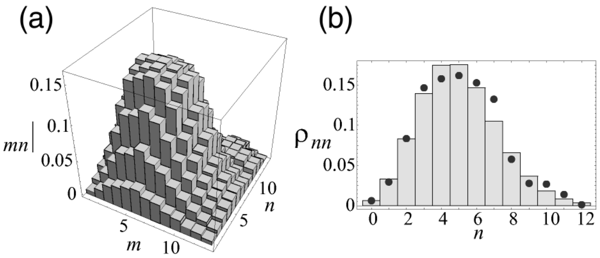

Fig. 4. (a) Absolute value of the density matrix elements in the Fock basis obtained by quantum state sampling of the marginal data shown in Fig. 3, (b) photon number distribution (dots) with a Poissonian distribution for the same average n (columns) shown for comparison.

In an experimental run, 262,144 experimental points were measured to provide 64 marginal distributions with 128 bins each [Fig. 3(a)]. The data acquisition was carried out with an Imtec T3012 12-bit analog-to-digital converter card running at a 33-MHz sampling rate in the memory segmentation regime. A 204-kHz pulse repetition rate was used, so the acquisition of each marginal distribution took ~20 ms. Because the setup was not interferometrically stable (we measured 8° average phase drift over time intervals that correspond to the complete measurement), in each distribution the actual value of θ during the measurement was calculated from the average of all quadrature values in the distribution.

We applied the inverse Radon transformation[16] with a cutoff frequency of 7.25 to the marginal data to obtain the Wigner function of the quantum state measured. The reconstructed Wigner function exhibits the expected two-dimensional Gaussian function of the quantum state distribution with a width equal to that of the vacuum state Wigner function. The ripples at the side of the main peak are numerical artifacts and are the result of various measurement errors.

We applied the quantum sampling method[16,17] directly to the raw experimental data to reconstruct density matrix ρ_{mn} of the state (Fig. 4). An average photon number of $\langle n \rangle = \sum n\rho_{nn} = 5.01$ photons per pulse, corresponding to a coherent excitation of $\alpha = 2.24$, is inferred from the measured photon number distribution. Unlike in the tomography in the continuous-wave regime,[5] these numbers do not refer to a frequency sideband of a bright coherent beam but directly correspond to an average number of photons in the signal laser pulse. The comparison of the reconstructed density matrix with that of an ideal coherent state with an amplitude $\alpha = 2.24$ yields a state preparation fidelity of $F = \langle \alpha | \hat{\rho} | \alpha \rangle = 0.995$.

In conclusion, we have designed and built a pulsed balanced homodyne detector for highly accurate time-domain quantum measurements. It exhibits a high bandwidth (1 MHz), >90% quantum efficiency, and very large (>85-dB) common mode rejection. As a demonstration of the capability of our measurement system, we have shown quantum tomography of a pulsed coherent state with a total measurement time of only 1.3 s. This detector will be of significant use in a variety of experiments in quantum optics; in particular, it has already been used for quantum tomography of the single-photon Fock states.[18] The detector could be adapted for shot-noise-limited absorption measurements at subnanowatt power levels because of its low technical noise.

We are grateful to S. Eggert for technical assistance. A. I. Lvovsky is supported by the A. von Humboldt Foundation. His e-mail address is alex.lvovsky@uni-konstanz.de.

*Present address, Institut für Experimentalphysik, Universität Düsseldorf, D-40225 Düsseldorf, Germany.

References

1. H. P. Yuen and V. W. S. Chan, Opt. Lett. **8,** 177 (1983).
2. R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley, Phys. Rev. Lett. **55,** 2409 (1985).
3. L. A. Wu, H. J. Kimble, J. L. Hall, and H. Wu, Phys. Rev. Lett. **57,** 2520 (1986).
4. D. T. Smithey, M. Beck, M. G. Raymer, and A. Faridani, Phys. Rev. Lett. **70,** 1244 (1993).
5. G. Breitenbach, S. Schiller, and J. Mlynek, Nature **387,** 471 (1997).
6. M. Vasilyev, S.-K. Choi, P. Kumar, and G. M. D'Ariano, Phys. Rev. Lett. **84,** 2354 (2000).
7. Z. Y. Ou, S. F. Pereira, H. J. Kimble, and K. C. Peng, Phys. Rev. Lett. **68,** 3663 (1992).
8. A. Furusawa, J. L. Sorensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble, and E. S. Polzik, Science **282,** 706 (1998).
9. G. T. Foster, L. A. Orozco, H. M. Castro-Beltran, and H. J. Carmichael, Phys. Rev. Lett. **85,** 3149 (2000).
10. D. T. Smithey, M. Beck, M. Belsley, and M. G. Raymer, Phys. Rev. Lett. **69,** 2650 (1992).
11. M. E. Anderson, M. Beck, M. G. Raymer, and J. D. Bierlein, Opt. Lett. **20,** 620 (1995).
12. K. Schneider, M. Lang, J. Mlynek, and S. Schiller, Opt. Express **2,** 59 (1998), www.opticsexpress.org.
13. P. K. Lam, T. C. Ralph, B. C. Buchler, D. E. McClelland, H. A. Bachor, and J. Gao, J. Opt. B **1,** 469 (1999).
14. E. M. Daly, A. S. Bell, E. Riis, and A. I. Ferguson, Phys. Rev. A **62,** 043807 (2000).
15. T. Hirano and M. Matsuoka, Opt. Lett. **15,** 1153 (1990).
16. U. Leonhardt, *Measuring the Quantum State of Light* (Cambridge U. Press, Cambridge, 1997).
17. G. M. D'Ariano, U. Leonhardt, and H. Paul, Phys. Rev. A **52,** R1801 (1995).
18. A. I. Lvovsky, H. Hansen, T. Aichele, O. Benson, J. Mlynek, and S. Schiller, Phys. Rev. Lett. **87,** 050402 (2001).