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# Quantum noise detection: A portable and educational system

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Quantum noise is a key feature of laser beams. It is both a limiting effect in contemporary optical measurements and a manifestation of the quantum nature of light. Its properties distinguish it from classical noise. We demonstrate a simple, reliable, and portable apparatus using low cost commercial lasers and electronics that provides evidence of these properties. 

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## I. INTRODUCTION: THE PROPERTIES OF OPTICAL QUANTUM NOISE

The quantum properties of light are often associated with wave-particle duality.[1,2] By using modern photodetectors it is possible to record the arrival of each photon in a beam as an individual event, if the photon flux is relatively low. This ability can be used to demonstrate some quantum effects, such as single particle interference.[3] The quantum nature of light also has consequences for the properties of much stronger beams.[4] Shot noise or optical quantum noise is the result of quantum fluctuations of the intensity of a laser beam. The formalism of quantum optics has been spectacularly successful in describing the quantum state of a laser beam, using the coherent state or Glauber state.[5] This formalism has been well tested and extended to include nonclassical or squeezed states of light[6] in which quantum noise is lowered for one property, for example, the phase, while increased for another, the amplitude; the total amount of uncertainty is kept constant.

In recent years many optical instruments have been perfected so that optical quantum noise, or shot noise as it has been called, is the dominant remaining source of noise. Quantum noise thus limits the signal-to-noise ratio for many optical tools such as absorption spectrometers,[7] interferometers,[8,9] and even laser pointers.[10] In brief, optical quantum noise is important as a fundamental consequence of quantum mechanics and as a limiting effect in the development of modern instruments.

In this paper we describe a method of detecting quantum noise in a teaching context and describe a convincing demonstration of the properties of quantum noise. The emphasis is on a simple, reliable, and low-cost apparatus using, whenever possible, readily available components.

There are three defining features of quantum noise[1,4] that allow a clear distinction between classical noise and quantum noise:

1. The quantum fluctuations of the intensity of a laser beam have a specific noise spectrum. The noise power is independent of the frequency at which it is detected. Such a spectrum is called white noise, and differs from many other noise sources which increase for lower frequencies, for example with a $1/f$ dependence.
2. Another property of quantum noise is the scaling of the noise variance with the intensity. For quantum noise the variance $V_{qn}$ scales as

$$V_{qn}(P) \sim P. \tag{1}$$

In contrast the standard deviation $\sqrt{V_{cl}}$ of classical noise is a fixed percentage of the total power. Hence,

$$V_{cl}(P) \sim P^2. \tag{2}$$

Likewise, the scaling law resulting from a modulation of the laser intensity is

$$V_{mod}(P) \sim P^2. \tag{3}$$

3. A feature of quantum noise is its behavior in relation to beam splitting. The classical fluctuations and modulations of the beam intensity are shared between the reflected and the transmitted beams, equivalent to Kirchoff's law in electrical circuits, and result in two perfectly correlated beams hitting the detectors. In contrast, quantum noise introduces uncorrelated noise. One way to understand this property is to remember that quantum noise comes from the random arrival of photons. The photons are not split in half by the beam splitter, but have a 50% probability to be transmitted or reflected. This randomness gives rise to uncorrelated noise in the detectors. If a laser beam is quantum noise limited and the classical noise is negligible, the noise in the two output beams from the beam splitter is completely uncorrelated.

In our experiment we demonstrate properties (2) and (3). The spectral properties (1) can be demonstrated using an electronic spectrum analyzer, but this kind of device is outside the scope of most teaching laboratories. To demonstrate the scaling and correlation properties, a light source with as little classical noise as possible is necessary. Such a source is readily available as a low-cost diode laser. Detectors and amplifiers that contribute less electronic noise than quantum noise are also required. For this purpose we use photodetectors with custom-made preamplifiers and commercial low noise amplifiers.[11,12] A conventional oscilloscope is used to

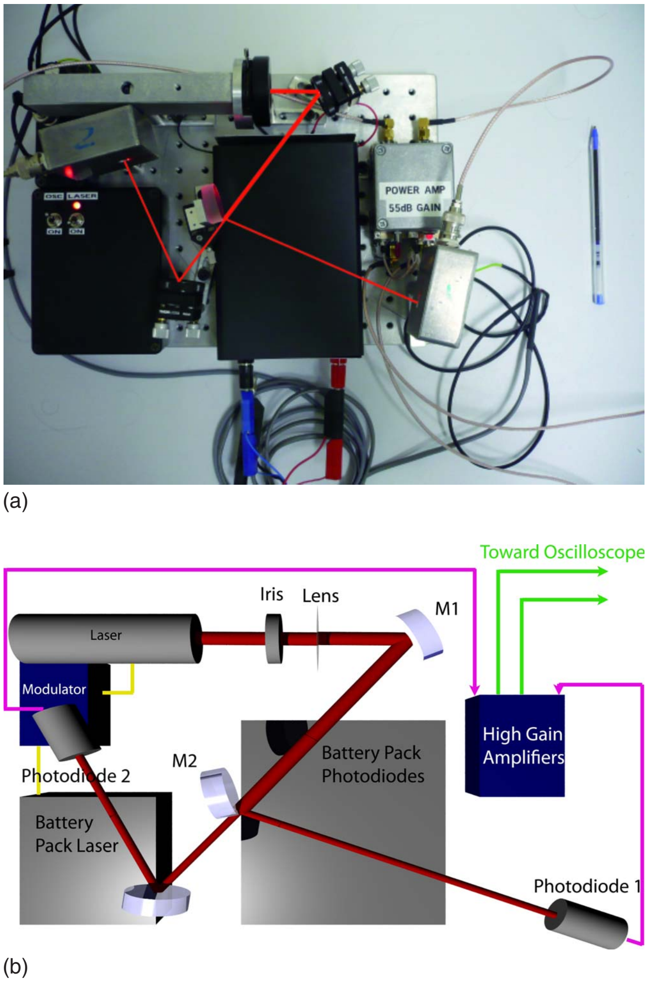


Fig. 1. The total laser beam power is adjusted using an aperture in front of the laser source. The laser intensity is modulated using a custom-built amplified crystal oscillator which produces a sinusoidal modulation at 2 MHz. The two beams are simultaneously detected by photodiodes 1 and 2 and the amplified signals are displayed on an oscilloscope in *x*-*y* mode.

detect the output signal, and a straightforward analysis method is available using an oscilloscope with an *x*-*y* display.

The apparatus shown in Fig. 1 enables us to measure both the correlation and scaling properties of optical quantum noise and to demonstrate some quantum features of light. Most optical experiments either focus on the frequency domain using spectrum analyzers and measure the noise spectrum of intense beams.[13] Alternatively, they focus on counting the clicks from individual photons with avalanche photodiodes[14] to study the correlations between the clicks from one or more detectors. Our design allows us to investigate correlations in an intense beam using a continuous noise signal.

## II. THE EXPERIMENT

Because the goal is to design a teaching and demonstration experiment, our emphasis is on simplicity. Accordingly, the apparatus is small (the entire experimental setup fits on a 210 mm $\times$ 300 mm breadboard) and uses a conventional oscilloscope. The trick is to use an oscilloscope as a detector for correlations. The laser beam is split into two beams 1 and 2 of equal power by sliding mirror M2 half-way across the beam. Each beam is detected separately and the photocurrents are amplified and displayed simultaneously on the $x$ and $y$ axis of the oscilloscope. If the two photocurrents, which are proportional to the intensities $I_1(t)$ and $I_2(t)$ of the beams, are correlated, the display will be on the diagonal axis. That is, correlated noise will be seen as fluctuations along the diagonal axis, at 45° to the $x$ and $y$ axes, if the intensities and gains in the two beams are the same. Uncorrelated noise will lead to independent fluctuations in both the $x$ and $y$ axes and produce a fuzzy area on the screen. For equal intensity and gain this area will be circular. The oscilloscope displays all frequencies up to its cutoff frequency or the detector's or the amplifier's. To demonstrate quantum noise we have to be very careful to avoid any extraneous noise, for example from stray magnetic fields. Reducing extraneous noise can be achieved by good design and electromagnetic shielding.

The apparatus employs a relatively low power laser diode pointer (~8 mW) emitting a beam at 632 nm with a slightly elliptical shape. The laser is housed in an aluminium casing secured to the custom-made aluminium breadboard. The laser beam intensity can be changed by adjusting the diameter of an aperture mounted directly outside the diode laser. The laser beam is then focussed by a lens (200 mm focal length) on the detectors to maximize the detection efficiency. After the lens the beam is reflected by mirror M1 and split into equal parts by a second mirror M2. One half of the beam is redirected onto the first photodetector while the other half misses the mirror and proceeds to the second photodetector. The beamsplitting mirror is mounted on a miniature translational stage (Thorlab MR 1.4) which allows it to move in and out of the beam and the splitting ratio to be adjusted. The mirror M2 could also be replaced by a half-silvered mirror, at the expense of loosing the ability to adjust the splitting ratio.

The two detectors are custom made and are matched to produce very similar outputs when exposed to the same power. The aim is to create the largest quantum noise signal and suppressing the electronic noise from the first amplifier inside the detector is critical. The direct current (dc) signals from the detectors are monitored to ensure that the power $P$ is equally split between the photodiodes; the alternating current (ac) signals are connected to a pair of high-gain/low noise commercial amplifiers (MITEQ, frequency 1–100 MHz). Several rechargeable battery packs make this system completely portable and reduce noise inputs from power supply. A picture and the layout of the system can be found in Fig. 1.

The laser intensity can be modulated with the electronic voltage created by the amplified crystal oscillator (IQXO-350). The degree of modulation is adjusted by the user. The modulation frequency must be high enough so that the modulated signal is not affected by low-frequency noise sources, including the $1/f$ noise resulting from the electronics, and is above the lower cutoff frequency of the amplifiers (1 MHz). The frequency also must not exceed either the maximum modulation frequency of the laser or push to the limits the low-noise amplifiers inside the detectors. For this reason an intermediate value of 2 MHz was chosen. Because the evidence of quantum noise that we seek does not depend on this modulation frequency, it remains fixed throughout the experiments.

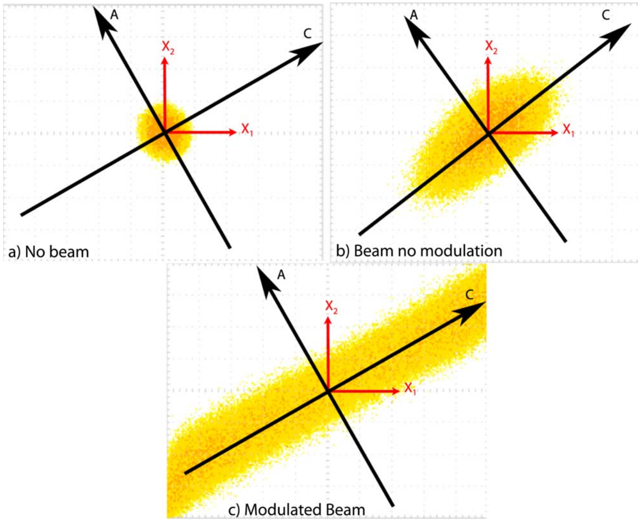


Fig. 2. Display of the oscilloscope used for measuring the noise and correlation. The $x$ and $y$ axis display the photocurrent generated by detectors 1 and 2, respectively. Any correlated noise will appear on the diagonal axis labeled C; any uncorrelated noise will appear equally on the A and C axes. (a) The laser is turned off, (b) the laser beam at 8 mW without modulation, and (c) the laser beam at 8 mW and maximum modulation.

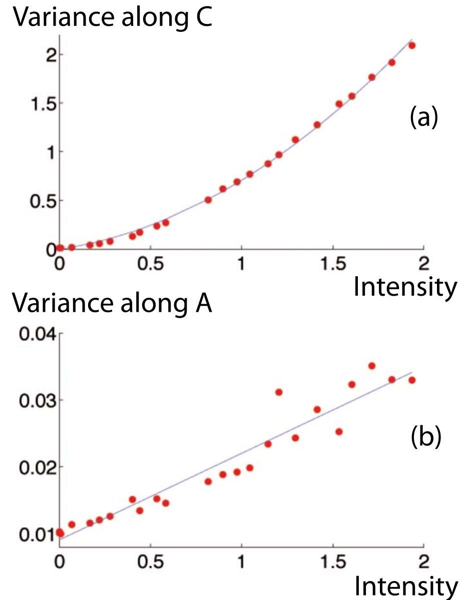


Fig. 3. Variance of the intensity fluctuations as a function of the average intensity of the beam in photocurrent units. (a) The variance along the correlated axis with a quadratic dependence on the intensity. (b) The variance along the anti-correlated axis with a linear dependence on the intensity.

## III. RESULTS

With the two photodiodes aligned and the laser turned on, the two signals originating from the photodetectors are displayed in $x$-$y$ mode. Different investigations are possible by varying the intensity of the beam and the modulation amplitude.

The electrical noise, that is, dark noise, of the detectors and amplifiers is first measured by turning the laser off. This noise calibration is critical because we need the quantum noise to be significantly larger than the dark noise.

By turning on the laser without introducing any modulation, the beams create additional fluctuations. They are the result of the optical quantum noise for which the two signals from photodiode 1 and 2 are uncorrelated and the residual classical noise in the laser. This classical noise introduces correlations between the two photodiode channels. Figures 2(a) and 2(b) show oscilloscope traces of the signal for no beam, that is, dark noise, and for an 8 mW beam, respectively.

Noise along the C axis is correlated noise, and noise along the A axis is anticorrelated. The C axis is not perfectly at 45° because the gains of the amplifiers are not perfectly balanced. Both dark noise and quantum noise, because they produce noncorrelated signals on the two detectors, introduce fluctuations equally on the A and C axes. In contrast, classical noise and modulation of the laser intensity introduce correlations between the two signals and give fluctuations only on the C axis. Thus, a comparison of Figs. 2(a) and 2(b) makes it easy to evaluate the different components of the noise encountered. Along the A axis the difference of the noise level between Figs. 2(a) and 2(b) can be attributed to quantum noise. This simple comparison provides us with a first demonstration of the uncorrelated nature of quantum noise and a clear assessment of the quality of the detectors. We show a ratio of 3.5 between the variance of the noise from a 8 mW beam and the variance of the electrical noise, without filtering the output signal. Using bandpass filters in the 3–5 Mhz range improves the ratio to 5.5, and introduces phase differences between the two output signals. These phase differences do not allow for a clear linear shape when introducing modulation and thus were not used in our measurements. Second, comparing the noise levels along the C and A axes in Fig. 2(b) emphasizes the correlated nature of the classical noise of the beam.

Further analysis is possible by using the modulator, which introduces strong classical fluctuations. Their correlated nature is obvious in Fig. 2(c), with overextended fluctuations along the C axis, while fluctuations along A remain similar to Fig. 2(b). Thus, the analysis of several oscilloscope traces demonstrates the uncorrelated nature of quantum noise. By setting the modulation amplitude to the maximum value below the amplifier's saturation and changing the average beam intensity, it is possible to observe the scaling laws. Figure 3 shows the variance of the fluctuations as a function of the beam intensity. We observe both the linear scaling of the quantum noise and the quadratic scaling of the classical noise.

Finally, recording the trace is possible, either by using a digital oscilloscope with relevant connectivity (for example a Tektronix TDS 2004 B) or a USB oscilloscope (Voltcraft DSO-220 USB). The distribution of the data points recorded with a modulated beam provide further confirmation of the correlated nature of classical fluctuations. As can be seen in Fig. 4 the shape of the distribution is clearly non-Gaussian along the C axis because it is the result of the sinusoidal modulation of the intensity. In contrast, along the A axis, the distribution remains Gaussian, thus indicating that no fluctuations on the A axis result from the modulation. The A axis is thus truly uncorrelated noise, that is, dark noise and quantum noise. If we consider that the total fluctuations of the signal are a result of the modulation, classical noise, dark noise, and quantum noise, the fit of the theoretical distribution to the data gives very accurate results.

In conclusion, our simple experiment provides evidence of

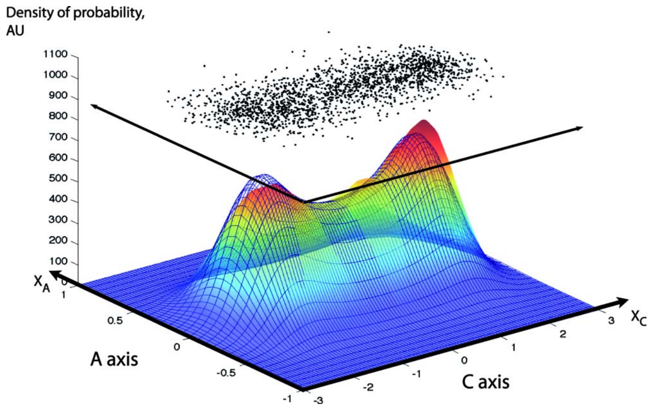


Fig. 4. The distribution of the measurements is non-Gaussian as a result of the sinusoidal modulation. The black dots are the measurements results (only one fifth of the actual sample is shown), and the full surface is the measurement's density. The wired surface is a theoretical distribution which accounts for all the noise terms discussed in the text.

the properties of quantum noise in intense beams. It can also be used as a benchmark to compare the performance of equipment to the quantum noise limit.

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