Towards the Improvement of the Heterodyne Receiver Sensitivity beyond the Quantum Noise Limit

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Abstract—**Noise reduction in heterodyne receivers of the terahertz range is an important issue for astronomical applications. Quantum fluctuations, also known as shot noise, prohibit errorless measurements of the amplitude of electro-magnetic waves, and introduce the so-called standard quantum limit (SQL) on the minimum error of the heterodyne measurements. Nowadays, the sensitivity of modern heterodyne receivers approaches the SQL, and the growing demand for the improvement of measurement precision stimulates a number of both theoretical and experimental efforts to design novel measurement techniques aimed at overcoming the SQL. Here we demonstrate the first steps towards the practical implementation of a sub-SQL quantum receiver. As the principal resources, it requires a highly efficient single-photon counting detector and an interferometer-based scheme for mixing the signal with a low-power local oscillator. We describe the idea of such receiver and its main components.**

The ultimate fundamental limits of the measurement precision are studied in the fields of quantum physics, quantum radiophysics and quantum optics for many years. It is well understood that the quantum fluctuations of the signal, such as shot noise, lead to the finite measurement precision even in the absence of the technical noise and introduce the unavoidable signal discrimination error. Back in the 60s of the last century, the fundamental limit on the maximum accuracy of quantum measurements was calculated [1, 2], nowadays called the Helstrom bound, which turned out to be much smaller than the corresponding value provided by the ideal heterodyne receiver (called the standard quantum limit, SQL). Since then, a number of efforts were made to design a realistic setup to achieve the Helstrom bound, or, at least, to overcome the SQL. The Helstrom bound depends on the number of circumstances, for instance, the quantum state of the signal and *a priori* knowledge about the signal parameters, such as polarization, spectrum, spatial profile, timing, photon statistics, *etc*. The basic idea of overcoming the SQL is to take into account this *a priori* information about the signal, and design a measurement scheme specifically suited for the given type of signal.

Despite the Helstrom bound is known for several decades, the problem of designing a realistic measurement apparatus able to achieve the Helstrom bound remains open. Over the past 50 years, several approaches to reduce the measurement error below the SQL were proposed [3, 4, 5]. The key components of the receivers that, in principle, can beat the SQL, include highly efficient single-photon counting detectors [6, 7] and various interferometer-based schemes for mixing the signal with a weak local oscillator, controlled by feed-back or feed-forward loops.

To date, implementation of heterodyne detection using a weak local oscillator (whose power is equal or slightly higher than that of the signal) has been demonstrated, with a low noise photon counters used as a detector. Photon-counting nature of the detector ensures quantum-limited sensitivity, provided 100% photon detection efficiency. In the IR-range, superconducting nanowire single photon detectors (SNSPDs) are widely used due to their remarkable characteristics. Such detectors have quantum efficiency close to 100%, and also high counting rate (limited by the dead time of ~ 10 ns). In the direct detection mode the detector count probability is time independent (i.e., registration of a photon is equiprobable in any given time interval).

In contrast to that, in the heterodyne mode, the probability of detecting a photon periodically changes with time, which is the result of the interference beats of the signal and the local oscillator. Processing of statistics of photocounts allows reconstruction of the frequency response of the signal. A heterodyne receiver based on SNSPD was demonstrated in [8]. The receiver was assembled using standard optical fibers (Fig. 1). As the signal and the local oscillator (LO) we used 1550 nm DFB-lasers. The IF analog signal read out from the detector was processed with help of RF spectrum analyser. However, this method of processing was not optimal.

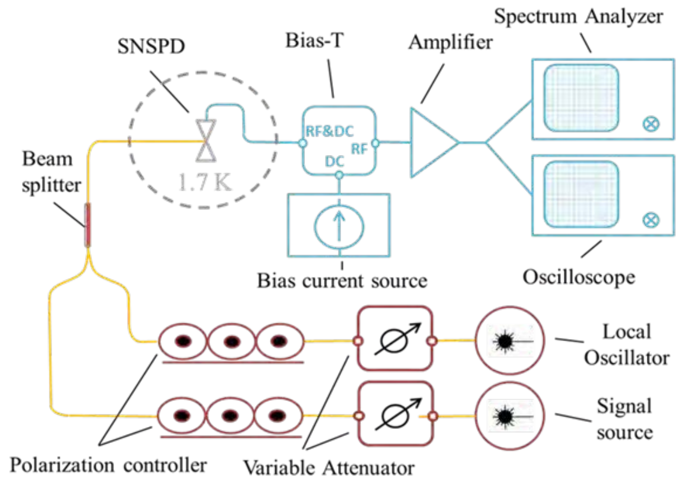

Fig. 1. A schematic view of the heterodyne receiver based on SNSPD

In [9], a similar measurement but implementing a digital post-processing of the signal was carried out. The voltage pulses from the detector were replaced by the delta pulses (since we are only interested in the registration of the photon arrival time moments), after which the Fourier transform was used to reconstruct the spectrum of the signal (Fig. 2).

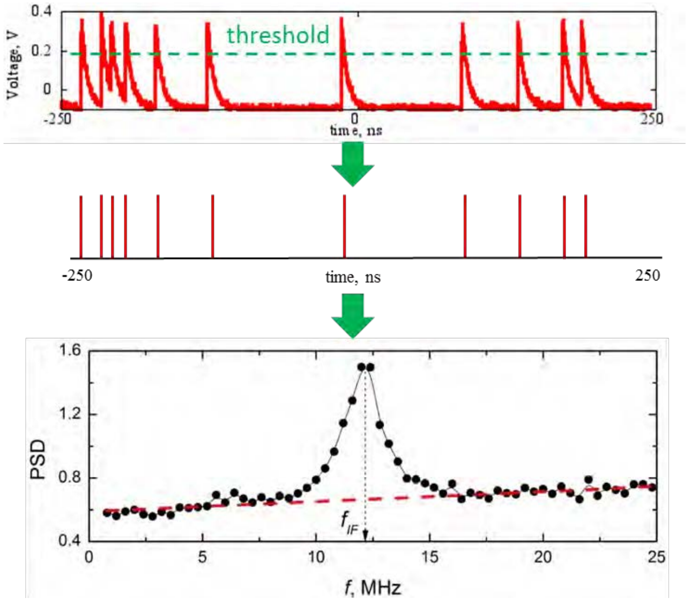

Fig. 2. Digital post-processing: first step – detection of photons, second step - the voltage pulses are replaced by delta-pulses, third step – Fourier-spectrum reconstruction.

The application of this approach makes it possible to get rid of the electrical component of noise, as well as the pulse spectrum contribution. Noise in such a system will be only dependent on the false response (dark counts), which provides a relatively insignificant contribution (dark count rate is 10^{-2} s^{-1}). Such a heterodyne receiver operates at the quantum noise limit, and the local oscillator power necessary for optimal operation is comparable to the signal power.

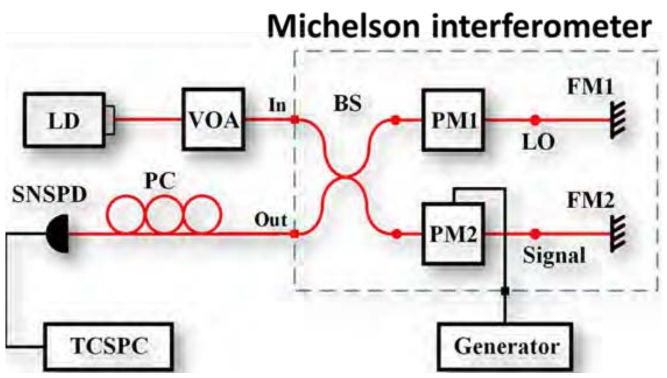

Fig. 3. Experimental setup: LD - Laser Diode at 1550 nm wavelength; PM1 and PM2 - phase modulators; TCSPC - Time-Correlated Single Photon Counting electronics, BS - beam splitter 50/50; FM1 and FM2 - Faraday's mirrors; VOA - variable optical attenuator; PC - polarization controller; SNSPD - Superconducting Nanowire Single-Photon Detector,

Recently, we proposed a novel approach to reduce the measurement error below the SQL [5]. With a new quantum receiver scheme based on the adaptive heterodyne technique, we can unconditionally suppress the measurement error below the SQL down to the Helstrom bound. In this work, we elaborate the idea further on and demonstrate the first steps of a proof-of-principle experimental realization of the sub-SQL receiver (see Fig. 3). Here we consider the simplest case – discrimination of a binary coherent signal, i.e. the task is to discriminate between two phase-conjugated states $|\alpha\rangle$ and $|-\alpha\rangle$. As a basis we use the Kennedy receiver scheme proposed in [3].

The main idea is the following. We interfere the signal and the LO on an almost transparent beam splitter (99:1 splitting ratio), such that almost all the power passes through the beam splitter. The LO power is chosen such that the reflected power of LO is comparable to the transmitted power of the signal (Fig. 4).

The result of interference between the LO and the signal can be tuned to be almost destructive, ideally leading to the completely nulling result. Such operation is called the nulling signal displacement. Ideal “nulling” occurs due to superposition of the signal with the LO of the same frequency, polarization, spatial profile, *etc*, but π phase difference. The ideally nulled signal provides no photon counts, thus the presence of photon counts after the interferometer is treated as 0 phase difference between the signal and the LO.

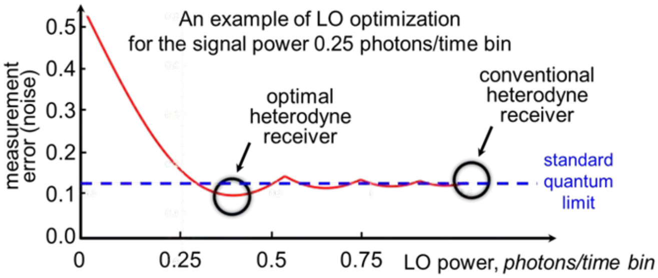

Fig. 4. Error rate as a function of the LO power for various heterodyne receivers. Optimized heterodyne receiver (global minimum) outperforms the conventional heterodyne receiver.

The optical part of the receiver is realized on the basis of the Michelson interferometer made of standard optical fiber components. We got an interference contrast of 25 dB with a temporal stability of a few seconds. As a source, a 1550 nm fiber-coupled DFB laser is used, serving as both the LO and the test signal, which is a typical technique used in similar receivers. The laser power is split by an optical fiber beam splitter. Then the signal is highly attenuated by a variable attenuator down to the single-photon level.

Using a fiber phase modulator installed in one arm of the interferometer, a binary test signal (periodically repeated "01" sequence at 100 kHz repetition rate) is produced. The result of the interference between the signal and the LO is either destructive or constructive, corresponding to zero photon counts (regarded as logical "0") and non-zero photon counts (regarded as logical "1", respectively). Photons are detected by the SNSPD, and the electronics registers the arrival time of the photon, counted from the beginning of the measurement.

To calculate the amount of errors, we send a signal with a known sequence of "0" and "1" to the receiver, and compare it with the measured sequence. After processing the results, the number of errors is normalized to the number of transmitted signal bins, and the error probability is compared to the SQL, which was calculated by the formula [1]:

$$e_{SQL} = \frac{1}{2}\left(1 - erf\left(\sqrt{2n}\right)\right), \qquad erf(x) = 2\int_0^x e^{-t^2} dt/\sqrt{\pi}$$

For the approximate average power of 1 photon per time bin, the observed state discrimination error (1.9%) was 27% below the SQL (2.6%). Thus, we were convinced that a receiver based on standard optical fibers and SNSPD can operate below the SQL, though we do uncorrected for the quantum efficiency of the detector (around 65%) and the losses in the interferometer. Based on the obtained results, in the future work aimed to attain the Helstrom bound, we plan to create a receiver with a tunable signal displacement and an adaptive feed-forward control of the LO. Development of the single-photon detector technology in the near- and mid-infrared range allows for realistic implementation of a new heterodyne receiver technique in this spectral range. Attempts are made to develop the single photon counting technology in a longer wavelength range [10], which opens good perspectives for the development novel receivers in far-infrared and THz ranges.

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