

Quantum Receiver beyond the Standard Quantum Limit of Coherent Optical Communication

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(Received 20 March 2011; published 24 June 2011)

The most efficient modern optical communication is known as coherent communication, and its standard quantum limit is almost reachable with current technology. Though it has been predicted for a long time that this standard quantum limit could be overcome via quantum mechanically optimized receivers, such a performance has not been experimentally realized so far. Here we demonstrate the first unconditional evidence surpassing the standard quantum limit of coherent optical communication. We implement a quantum receiver with a simple linear optics configuration and achieve more than 90% of the total detection efficiency of the system. Such an efficient quantum receiver will provide a new way of extending the distance of amplification-free channels, as well as of realizing quantum information protocols based on coherent states and the loophole-free test of quantum mechanics.

DOI: 10.1103/PhysRevLett.106.250503

PACS numbers: 03.67.Hk, 42.50.Ex

Coherent communication systems achieve the best signal-to-noise ratio in conventional optical communications based on laser light. It consists of coherent-state carriers with quadrature amplitude modulation (QAM) and a coherent receiver based on homodyne detections [1]. QAM provides the largest signal distances in phase space under the power constraint, while a coherent receiver detects them at the standard quantum limited (SQL) sensitivity. The SQL in optical communication is naturally defined as the lowest average error probability obtainable by directly measuring the modulated physical observable of coherent states. For example, an ideal photon counter reaches the SQL for intensity modulation signals (often called the shot noise limit), while an ideal coherent receiver reaches the SQL for QAMs. However, this is not the fundamental quantum limit of optical communication.

One approach to overcome such a limit is to use eigenstates of the observables, such as a photon number state for intensity modulation or an (infinitely) squeezed state for QAM, as carriers [2]. For noiseless channels, these non-classical carriers could completely circumvent the errors due to quantum noise and, in principle, realize an error-free communication. In practice, however, these states are extremely fragile to losses and easily turned out to be noisy mixed states and thus will not work in realistic channels. Another approach is to keep using coherent states as carriers but to optimize the measurement process. A coherent state is robust against the linear loss (which is inevitable in optical channels) and does not lose its coherence. Quantum detection theory has predicted that the minimum error bound is exponentially smaller than the SQL [Fig. 1(a)] [3], and its implementation schemes have also been proposed [4–8]. However, though some proof-of-principle

demonstrations have been reported [9–11], no unconditional experimental evidence surpassing the SQL of coherent communication has been reported yet.

In this Letter, we demonstrate for the first time a quantum receiver outperforming the SQL of coherent optical communication, i.e., the limit of current optical communications, in a lossy channel. We consider the simplest QAM signal set, binary phase-shift keyed (BPSK) coherent states $\{|\alpha\rangle, |-\alpha\rangle\}$ with equal prior probabilities. BPSK provides

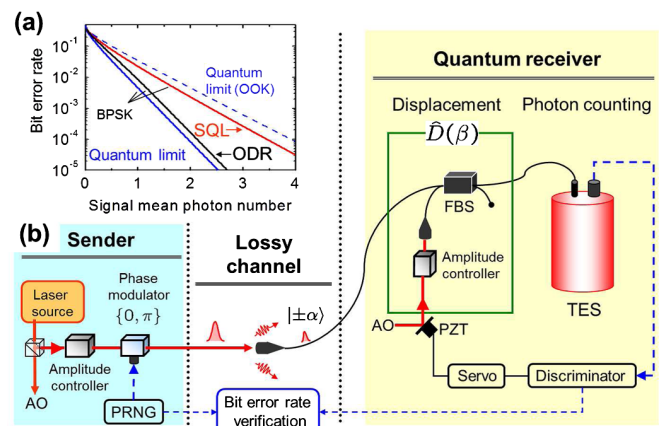


FIG. 1 (color online). (a) BERs for the BPSK coherent signals at the quantum limit (blue solid line), the SQL (red solid line), and detected by the ODR (black solid line). As a reference, the blue dashed line is the quantum limit for an OOK signal. The vertical axis corresponds to the signal mean photon number reached to the receiver. (b) Experimental setup. FBS, fiber beam splitter; AO, auxiliary oscillator; PRNG, pseudo-random-number generator; TES, transition-edge sensor; PZT, piezoelectric transducer.

the largest signal distance within any binary signals under the average-power constraint. Our receiver discriminates these signals with a bit error rate (BER) lower than that of the SQL.

The physical process of a near-optimal quantum receiver was first suggested by Kennedy [4] consisting of linear optics and photon counting. Soon after, it was extended to the exactly optimal one by Dolinar [5] (see also [3]) via application of an ultrafast feedback process. A proof of principle of the Dolinar receiver was recently demonstrated [9], where instead of the BPSK, intensity modulated [on-off keyed (OOK)] coherent signals $\{|0\rangle, |\alpha\rangle\}$ were discriminated under the shot noise limit. However, even if one could achieve the minimum error bound for an OOK signal discrimination, its error rate is still larger than the SQL for BPSK signals since the OOK is not an optimal modulation under the same power constraint [Fig. 1(a)]. Moreover, although in principle the feedback- (or feedforward-) based measurement can realize an arbitrary binary projection measurement [7], it is still challenging to outperform the SQL for BPSK signals via the feedback approach since it requires a detector simultaneously fulfilling a very high detection efficiency and an operation speed faster enough than the optical pulse width. Instead of the feedback, the optimal detection with an optical nonlinear process was proposed [6], but the required nonlinearity was far from the current technology.

Instead, we use a simpler receiver scheme without feedback such as Kennedy's near-optimal receiver [4]. The main obstacle to beat the SQL with the Kennedy receiver in practice is the fact that, for weak signals, its attainable BER is comparable to or even higher than that of the SQL [8]. The receiver scheme employed here is based on the recent proposal [8], which we call an optimal displacement receiver (ODR), solving the above problem, and its operation principle was demonstrated experimentally [10,11] though their performances could not reach the SQL due to technical problems, mainly the low detection efficiency ($\leq 70\%$) [10,11] and the low phase stability [11].

The experiment demonstrated here employs the ODR scheme and achieves more than 90% of the total detection efficiency as well as enough phase stability, mode matching, and low dark counts. To our knowledge, this is the highest total efficiency demonstrated in any photon-detection-based quantum information (and single-photon-level optical communication) protocols. Such a performance is realized by installing an efficient photon number resolving detector known as a superconducting transition-edge sensor (TES) [12–14]), almost error-free linear optics, and the TES-based phase stabilization.

The SQL of the BPSK signal with the average power $|\alpha|^2$ is expressed as the BER of $P_{\text{SQL}} = (1 - \text{erf}[\sqrt{2}\alpha])/2$, which is simply attained via a perfect homodyne detector. The optimal measurement achieving the quantum limit, on the other hand, is described by the projection onto the quantum superposition of signal states

$|\pi_-\rangle = b_0|\alpha\rangle + b_1|-\alpha\rangle$ and its complement in the signal space $|\pi_+\rangle$ [3]. Here, $b_0 = -\sqrt{P_{\text{QL}}/(1 - e^{-4\alpha^2})}$, $b_1 = \sqrt{(1 - P_{\text{QL}})/(1 - e^{-4\alpha^2})}$, and $P_{\text{QL}} = (1 - \sqrt{1 - e^{-4\alpha^2}})/2$ is the fundamental quantum limit of the BER. The superposition of coherent states is quite non-classical and is often called a “cat state” [15], which implies that the implementation of such a projector is a nontrivial task. The BERs P_{SQL} and P_{QL} are compared in Fig. 1(a), showing the high potential of the optimal quantum measurement.

We implement such a measurement approximately by a simple quantum receiver [8,10]. Suppose that coherent signals from the sender are attenuated in a lossy channel to be $|\pm\alpha\rangle$ and detected via the receiver. Our receiver consists of a linear displacement operation $\hat{D}(\beta) = \exp[\beta^*\hat{a} - \beta\hat{a}^\dagger]$ and a photon-counting device announcing two outcomes: zero or nonzero photons. Depending on these outcomes, the signal state is projected onto $|\omega_-\rangle = \hat{D}^\dagger(\beta)|0\rangle = |-\beta\rangle$ or its orthogonal space. Here β is optimized such that $|-\beta\rangle = e^{-|\beta|^2/2}(|0\rangle - \beta|1\rangle + \dots)$ approximates the nontrivial superposition $|\pi_-\rangle = e^{-\alpha^2/2}\{(b_0 - b_1)|0\rangle + (b_0 + b_1)\alpha|1\rangle + \dots\}$. In the ideal case, the optimal β is given as the solution of the equality $\alpha = \beta \tanh(2\alpha\beta)$. This ODR outperforms the SQL for any $|\alpha|^2$ and nearly reaches the quantum limit as illustrated in Fig. 1(a) [8,10].

Figure 1(b) shows an experimental setup for the optical communication in a lossy channel with the ODR. Continuous wave light from an external-cavity laser diode (wavelength, 853 nm; linewidth, 300 kHz) is highly attenuated and modulated by an electro-optic modulator to generate 20 ns pulses with a 40 kHz repetition rate. The pulses are split into two paths for the signal and the auxiliary oscillator (AO) for the displacement operation. At the sender's station, the signal amplitude control and the binary phase modulation are performed by two electro-optic modulators. The signal pulses are then propagated through a channel with a loss of -7 dB, where the loss is introduced by coupling the signal beam into a single-mode fiber with a low efficiency. The displacement operation $\hat{D}(\beta)$ at the detection part is realized by interfering the signal pulse with the AO pulse through a highly transmissive fiber beam splitter (FBS). The AO for the displacement is prepared to be a coherent state $|\beta/\sqrt{1-T}\rangle$, where T is the transmittance of the FBS and chosen as $T > 0.99$. The visibility at the FBS is measured to be $98.6 \pm 0.1\%$, which corresponds to the mode match factor of $\xi = 0.993 \pm 0.001$. The output from the FBS is guided into a TES to detect photons.

The superconducting TES enables us to resolve photon numbers with a very high detection efficiency. Its performance is characterized by the quantum efficiency and the energy resolution. Our TES is based on a titanium (Ti) superconductor, and its quantum efficiency is 0.95 ± 0.01

at 853 nm. This is achieved by carefully designing the surface (antireflection) and back-side (high-reflection) coatings and using a larger Ti device ($10 \times 10 \mu\text{m}^2$) which is coupled to the fiber with an almost unit efficiency (for details about our TES and its evaluation, see [14]).

The energy resolution characterizes the photon number resolution and is degraded by the electrical noise on the readout voltage pulse derived from Johnson noise and phonon noise in a TES. To increase the resolution, the noise in the output voltage waveform is reduced via a digital Wiener filter, which gives an energy resolution of 0.55 eV at 853 nm. The threshold discriminating the peaks of zero and nonzero photons is chosen in advance to minimize the incorrect guessing of photons due to the finite overlap of the energy distributions. An additional loss due to the overlap of the distributions was estimated to be 0.7%. We also directly observed the dark counts with the same threshold as $\nu = 0.003/\text{pulse}$.

The relative path length of the signal and the AO modes is actively stabilized by the signal laser and the TES before measuring BERs. To circumvent additional losses stemming from the additional probe beam and optics, the phase-locking loop is constructed by using the signal laser itself ($|\alpha|^2 \approx 2$) and photon counting via the TES with a digital feedback. At the phase locking step, the TES output is sent to a discriminator, and the number of clicks are counted for each 10 ms for the feedback loop. The stability is estimated to be within ± 0.057 rad. Additional losses in the receiver (the FBS and fiber splicings) are measured separately ($3.92 \pm 0.05\%$ in total), and, consequently, we estimate the total detection efficiency of our receiver as 0.91 ± 0.01 . The signal intensity $|\alpha|^2$ is calibrated by the TES with the uncertainty of 1% (see [11] for a detailed procedure).

Figures 2 and 3 show the main result of the BPSK signal discrimination via our quantum receiver. The phase of the signal is randomly prepared by a pseudo-random-number generator with equal probabilities, while the amplitude of the displacement β is kept in phase with $|\alpha\rangle$. Figure 2(a) shows typical sequences of the signal modulation and the TES output. The dashed line indicates a threshold for the signal decision, and the errors are highlighted by arrows. The TES output distribution with 10 000 trials is plotted in Fig. 2(b) for $|\alpha|^2 = 0.21$ and $|\beta|^2 = 0.59$. The red and blue plots are the outputs for $|\alpha\rangle$ and $|\beta\rangle$, respectively. The asymmetric distribution indicates the effect of the displacement since the original signals $|\pm\alpha\rangle$ have the same photon number statistics.

In Fig. 3(a), the β dependence of BERs is shown for the signals with a mean photon number of $|\alpha|^2 = 0.21$. Each point is obtained by 10 000 measurements (~ 250 ns). Error bars in the horizontal and vertical axes reflect statistically estimated standard deviations of the binomial distribution and the uncertainty of the signal power (1%), respectively. The other systematic uncertainty, such as relative phase drift during 10 000 measurements, is thought to be negligible. For $|\beta|^2 > |\alpha|^2$, the probability of

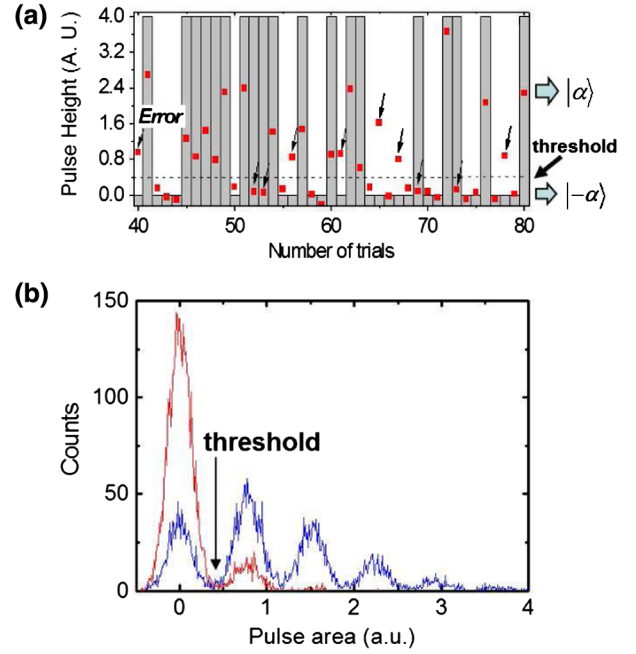


FIG. 2 (color online). (a) Random signal modulation (bar) and raw measurement data of the ODR (plot is the TES output pulse height). (b) The output pulse height distribution for the signals $|\alpha\rangle$ (red line) and $|\beta\rangle$ (blue line). $|\alpha|^2 = 0.21 \pm 0.01$ and $|\beta|^2 = 0.59 \pm 0.01$.

wrongly guessing $|\alpha\rangle$ ($|\beta\rangle$) is decreased (increased) by increasing $|\beta|^2$, and thus there is an optimal point minimizing the BER (the average errors) [11]. The experimental BER shows the dependence on β and at $|\beta|^2 \approx 0.6$, and it clearly outperforms the SQL (1.8 standard deviations from the SQL). Note that the data points do not employ any compensations for noises or detection losses. The experimental BERs make a good fit to the theoretical curve including imperfections of $\eta = 0.91$, $\nu = 0.003$, and $\xi = 0.993$ (dashed line) [8]. The experimental points are also compared to the SQL (homodyne detection) with the same detection efficiency ($\eta = 0.91$), showing the superiority of our receiver scheme. In Fig. 3(b), experimentally observed BERs with optimal displacements are plotted for different signal photon numbers. Again, the performance of our receiver clearly outperforms the SQL ($\eta = 1$) at $|\alpha|^2 = 0.21$ and is comparable to or slightly better than the SQL for the signals with $|\alpha|^2 \leq 0.4$. For higher signal photon numbers, the BERs deviate from the model calculation due to technical reasons, mainly the visibility degradation by the drift of polarizations in fibers. We should also note that the data shown here outperform homodyne detection with the same efficiency ($\eta = 0.91$) in a wide range of signal photon numbers.

In summary, our result shows the first unconditional observation of the error rate surpassing the SQL in coherent communication, that is, exceeding the theoretical limit of current optical communication technology. This will open up a new way of extending a link distance in amplification-free channels such as deep-space optical

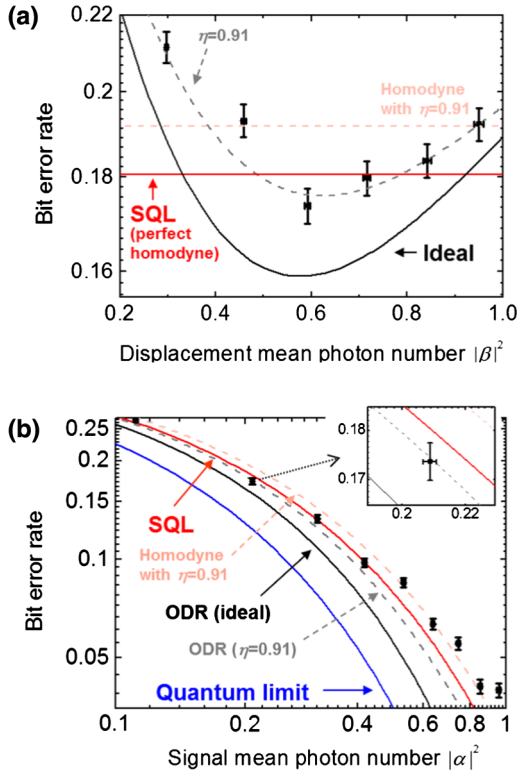


FIG. 3 (color online). (a) The measured BERs for various displacements. $|\alpha|^2$ is fixed to be 0.21 ± 0.01 . (b) The measured BERs obtained by the optimal displacement receiver for various $|\alpha|^2$. Theoretical curves are given for the quantum limit (blue solid line), the SQL (red solid line), the homodyne (pink dashed line, $\eta = 0.91$), the ideal ODR (black solid line), and the imperfect ODR (gray dashed line; see the text).

links, as well as reducing the number of amplifiers in long-haul optical fiber communication. Our scheme could be extended to multiple modulation signals [16] or another modulation format [17]. While the receiver demonstrated here measures each signal separately, an important future work is to extend it to quantum collective decoding [18–20], which collectively detects multiple pulses and is, in principle, reachable to the ultimate capacity bound in lossy optical channels [21]. From a technical point of view, our photon-level phase locking is an important step toward real communication and could also be useful for weak interferometric sensing.

Finally, it should be noted that our receiver has the ability to resolve photon numbers. The displacement receiver with a very high efficiency and number-resolving ability realized here is directly applicable to some important protocols on quantum information science and technologies, for example, recent proposals on a loophole-free test of quantum mechanics with continuous variable states [22], an efficient receiver for coherent-state-based quantum cryptography [23], and quantum repeaters and computation based on entangled coherent states [24–26].

We thank H. Takahashi, E. Sasaki, and T. Itatani for their technical support and J. Neergaard-Nielsen for reading of

the manuscript. This work was supported by MEXT Grant-in-Aid (No. 22740720) and JSPS, the FIRST program.

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