Single Rail Optical Quantum Computation Program

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PROGRAM DESCRIPTION

The potential of linear optical systems for quantum computation has been clearly illustrated by recent demonstrations of the operation of non-deterministic photonic CNOT gates. The aim of this program is to develop the technologies and techniques required for alternative encoding and detection schemes for Optical Quantum Computation (OQC).

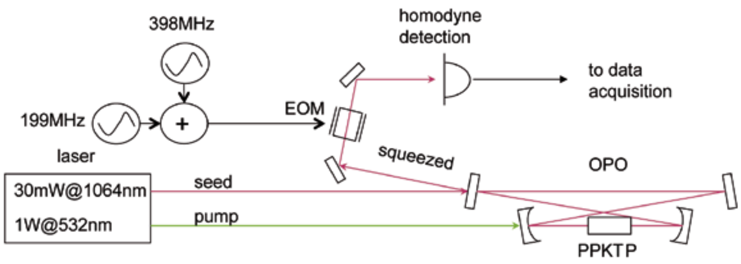

FIGURE 1

A schematic diagram of the source of the multiplexed quantum communications scheme.

1. Multiplexed, high-speed quantum communication over a quantum channel

In quantum information systems it is of particular interest to consider the best way in which to use the non-classical resources consumed by that system. Quantum communication protocols are integral to quantum information systems and are amongst the most promising near-term applications of quantum information science. Here we consider the issue of making the best use of quantum resources in the context of high-capacity, multiplexed quantum communications.

One particularly useful optical non-classical state for quantum communications is the squeezed vacuum, which exhibits reduced noise relative to a classical channel in one measurement quadrature at the cost of increased noise in the orthogonal quadrature. Simple passive operations can create entanglement, a key quantum resource, from squeezed vacua. With the addition of photon counting other key resource states such as single photons and cat states can be heralded from squeezed vacua. Hence the study of quantum channels based on squeezed vacuum states can lead to a quite general understanding of the requirements of quantum communication channels.

In spite of its name, a squeezed vacuum actually carries photons. So the spectral properties of the squeezed vacuum must be well matched to the digital signalling scheme in order to avoid consuming non-classical resources (i.e. photons) unnecessarily. We have shown theoretically that a comb of squeezing can support a greater multiplexed channel capacity per photon than a source of broadband squeezing with the same analogue bandwidth. We have created such a channel using the experimental setup shown in Figure 1.

The output of the OPO is sent to a homodyne detection system with an analogue bandwidth of 2.5 GHz. The homodyne measurement is digitally sampled at 8 GS/s, which is sufficient for time-resolved homodyne detection. For the purposes of producing a frequency-resolved view, the discrete Fourier transforms (DFTs) of 12207 time-resolved measurements of 1.024 μs duration are computed and their magnitudes averaged. The resulting frequency spectrum is shown in Figure 2. The variances of the squeezed and anti-squeezed output of the OPO are shown relative to the measured quantum noise limit (QNL). The first dozen teeth in the comb of squeezing are clearly observed in Figure 2.

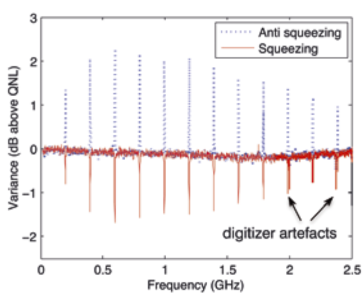

FIGURE 2

The measured noise spectra of the multiplexed quantum communications channel.

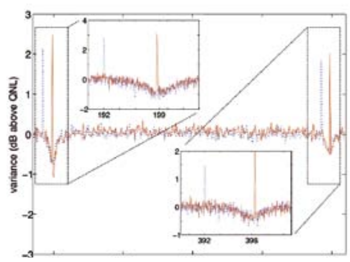

FIGURE 3

The measured signal to noise ratios of the frequency-division multiplexed communications scheme.

We illustrate the principle of multiplexed communication on the quantum channel by implementing frequency-division multiplexing on the first two resonances of the squeezing spectrum. Figure 3 shows the measured frequency spectrum of the scheme. The solid (dashed) trace shows measurements relative to the QNL when the carrier frequencies are (not) aligned with the resonances in the squeezing spectrum, 199 and 398 MHz (192 and 392 MHz) respectively. The improved signal to noise ratio, and hence channel capacity (0.65 vs 0.5), when the signalling and squeezing spectra are aligned is clearly observed. The insets to Figure 3 show a separate zoomed-in view of each independent frequency band.

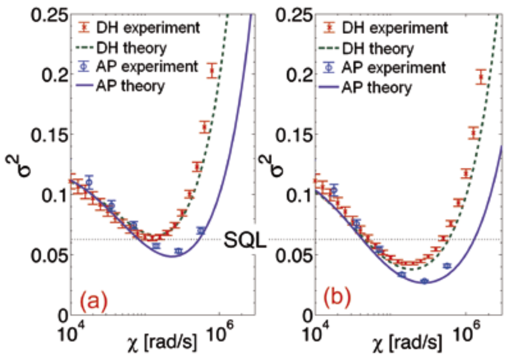

FIGURE 5

The experimental and theoretical variance of the four phase estimation techniques: filtered dual homodyne (DH) and adaptive phase (AP) in part (a); and smoothed DH and AP in part (b).

2. Quantum parameter estimation

Quantum parameter estimation (QPE) is the problem of estimating an unknown classical parameter or process, and it plays a role in the preparation or dynamics of a quantum system. QPE has many applications, from gravitational wave detection to quantum computing and beyond to quantum key distribution. One of the key issues in QPE is the development of practical methodologies which allow measurements to approach or exceed the standard quantum limit (SQL) for a given measurement strength.

The problem of estimating a classical process dynamically coupled to a quantum system under continuous measurement has recently been generalised, with three main categories of quantum estimation being introduced. Those categories are: prediction or filtering, smoothing, and retrodiction. Of those, prediction or filtering is a causal estimation technique that can be used in real-time applications. Smoothing and retrodiction are acausal and so cannot be used in real time, but they can be used for off-line data processing or with a delay corresponding to the estimation time.

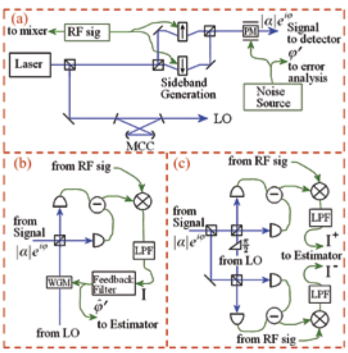

FIGURE 4

A schematic diagram of the quantum parameter estimation experiment.

Smoothing, in which the signal is inferred at a point in time based on data taken both before and after that time, is the only time-symmetric estimation technique. As a consequence, it can be more precise than the time asymmetric techniques of filtering or retrodiction. Such a result is very significant for quantum sensing applications where it is more important to have precise rather than real-time estimates.

Here we present the first experimental demonstration of QPE using quantum smoothing. Specifically, we consider estimation of the phase of a continuous optical field, which is the prime example of QPE due to its wide-ranging technological relevance. According to our new theory, adaptive measurements and smoothing both offer improvements over the alternative (non-adaptive and filtering respectively). Moreover, using both together offers the maximum improvement, with a mean-square phase error smaller than the standard (non-adaptive, filtered) quantum limit by a factor of up to 2√2 in theory for pure phase diffusion.

We have made the first experimental verification of the quantum theory of continuous adaptive phase estimation using the setup shown in Figure 4. The measured and predicted mean-square errors for the four different estimation techniques are shown in Figure 5. The values used in the theoretical predictions are determined from calibrated measurements of the system phase. Figure 5 shows good agreement between theory and experiment for all the estimation techniques. It demonstrates that phase estimation by quantum smoothing is significantly better than that from quantum filtering. As predicted, the improvement is nearly a factor of two at the optimum for both the adaptive and dual homodyne measurements.

As predicted, adaptive phase estimation outperforms dual homodyne measurement by a factor of approximately √2. The theory curves here take into account the known imperfections, but the horizontal line indicating the SQL is defined (as above) in terms of the actual photon flux, and corresponds to what would be achievable by ideal dual-homodyne filtering. Adaptive measurements perform better than the SQL for both types of estimator, with a maximum improvement by a factor of 2.24 ± 0.14 over the SQL.