論文の内容の要旨

論文題目: **Research on non-classical states experimental quantum teleportation: conditional operations, theoretical model and tomography algorithms**

(非古典状態の量子テレポーテーション実験の研究
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条件付き操作、理論モデル、トモグラフィアルゴリズム)

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1. Introduction

As a striking example of quantum algorithm, teleportation was discovered early on in the development of the field of quantum information processing. With either qubit [1] and continuous variable flavor [2], experiments were soon to follow [3, 4]. Quantum teleportation turns out to be an especially interesting primitive for prototyping experimental setups of quantum information processing. As was discovered in [5], it is possible to merge any Gaussian quantum gate together with the teleportation copying operation. An idea which has now evolved into the paradigm of one-way quantum computing and cluster state computation. Although Gaussian operations alone are not sufficient to achieve universal quantum information processing[6], several proposals have been made to mix together these one-way operations with non-Gaussian input states to achieve such universal operations [7–9]. These hybrid paradigm techniques are currently one of the most active area of research in quantum optics. With this long-term objectives of hybrid quantum operations, the research work of this thesis has been focused on the quantum teleportation of Schroedinger's cat states of light. Until now the continuous variable version of teleportation has indeed only been performed with Gaussian states, in a monomode sideband regime. There was a lack of results and understanding in this particular area, both experimentally and theoretically, and a lack of experimental research for relevant applications in quantum information processing. In the duration of this thesis, we have been able to demonstrate several results linked directly to these topics[10–12].

2. Non-Gaussian state generation and teleportation

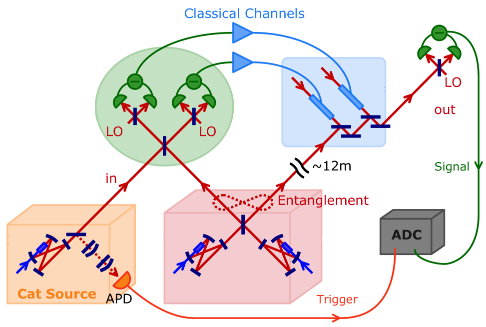

Figure 1: Quantum teleportation of photon subtracted squeezed vacuum states, experimental setup.

We have demonstrated the experimental preparation of non-classical states of light closely approximating Schroedinger's cat states, with experimentally measured negative Wigner functions. We have also demonstrated the quantum manipulation of this fragile states and performed quantum teleportation of Schroedinger's cat states while preserving the quantum nature of these states at the output of teleportation[10]. To accommodate with the required time-resolving photon detection techniques and handle the wave-packet nature of these optical Schroedinger's cat states, we have developed a hybrid teleporter built with continuous-wave light yet able to directly operate in the time domain (see Fig.1). Both setups are individually evolved from the experimental setups of [13] and [14]. As a prototype of these new techniques in a fully quantum regime, this experiment constitutes a first step towards more advanced QIP protocols and future non-classical state manipulation experiments. Indeed although Schrödinger's cat states are often quoted for their potential applications[15, 16], the major experimental challenge of actually using and manipulating these fragile states has remained mostly unaddressed until this experimental demonstration.

Successfullness of continuous variable teleportation is a non-trivial problem as it is closely related to the kind of input states and entanglement used. For the Gaussian case, the fidelity $F = \langle\psi_{in}|\rho_{out}|\psi_{in}\rangle$ is the usual figure of merit, though F losses much of its meaning for non-Gaussian mixed states. Because non-classicality itself is an ambiguous propertie, the problem is even more complex when the input state is a Schroedinger's cat state. To verify the success of Schroedinger's cat states teleportation we perform experimental quantum tomography of the input and output states independently (see Fig. 2). We consider the input W^{in} and output W^{out} Wigner functions and adopt the criteria of negativity teleportation in W^{out} given W^{in}. The reconstructed input Wigner function W^{in} shows the two positive Gaussians of $|\alpha\rangle$ and $|-\alpha\rangle$ together with a central negative dip ($W^{\text{in}}(0,0) = -0.171 \pm 0.003$) caused by the interferences of the $|\alpha\rangle$ and $|-\alpha\rangle$ superposition. The output Wigner function W^{out} retains the characteristic non-Gaussian shape as well as the negative dip ($W^{\text{out}}(0,0) = -0.022 \pm 0.003$) to a lesser degree. The degradation of the central negative dip and the full evolution of W^{in} towards W^{out} can be fully understood as we explain in Sec. 3. We calculate that the fidelity F_{cat} is as high as 0.750 ± 0.005 for the input Wigner function W^{in} with the nearest Schrödinger's cat having an amplitude equal to $|\alpha_{\text{in}}|^2 = 0.98$. However, after the teleportation W^{out} fidelity is reduced to 0.46 ± 0.01 with the nearest Schrödinger's cat state having an amplitude $|\alpha_{\text{out}}|^2 = 0.66$.

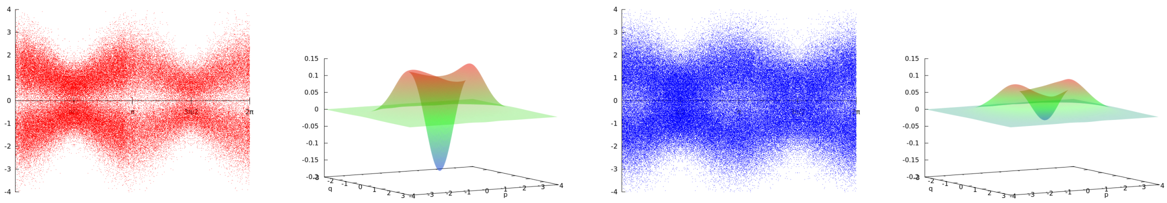

Figure 2: Quantum teleportation of photon subtracted squeezed vacuum states, experimental results. From left to right, input state electrical field, input state Wigner function, output state electrical field, output state Wigner function.

3. Multimode model of teleportation

Although Gaussian states teleportation has been amply studied, due to the complex nature of non-Gaussian states and especially mixed non-Gaussian states, only few general results exist for this particular case. On top of these difficulties, to accommodate with the transient nature of our non-Gaussian input state used, the teleporter we used operates over a broad range of frequencies. Our main objective was to answer both these issues with a theoretical model as simple and efficient as possible[11]. In the Braunstein-Kimble teleportation scheme described in [17], the teleportation is expressed in phase space by the convolution $W^{\text{out}} = W^{\text{in}} \circ G_{e^{-r}}$ with r the EPR correlation parameter and $G_\alpha(q,p)$ a normalized Gaussian of standard deviation α. In this case teleportation of non-classical features such as negativity requiers 3 dB ($r = \ln\sqrt{2}$) of squeezing[18], or equivalently a vacuum fidelity of $F \geq 2/3$, which is also called the no-cloning limit. Various monomode and multimode models exist for the protocol of photon subtraction that we use to generate our experimental non-classical state [19, 20]. In the limit of small s and R, they are essentially equivalent and therefore we will assume that an APD trigger projects our input state onto a squeezed photon $\hat{S}_s|1\rangle$. The Wigner function W^{ref} of this state is written $W^{\text{ref}}(q,p) = 2(e^{2s}q^2 + e^{-2s}p^2 - 1/2)G_{1/\sqrt{2}}(e^s q, e^{-s}p)$. Although not pure our experimental input state happens to fit extremely well a simple loss model where the experimental Wigner function W^{in} can be deduced from W^{ref} by applying "beam splitter losses" $1-\eta$ equivalent in phase space to $W^{\text{in}}(q,p) = \left(W^{\text{ref}} * G_\lambda\right)(q/\sqrt{\eta}, p/\sqrt{\eta})/\eta$ with $\lambda = \sqrt{\frac{1-\eta}{2\eta}}$. W^{out} is then written in the same form as W^{in} and reads $W^{\text{out}}(q,p) = \left(W^{\text{ref}} * G_{\lambda'}\right)(q/\sqrt{\eta}, p/\sqrt{\eta})/\eta$ where λ has been changed to $\lambda' = \sqrt{\lambda^2 + \left(e^{-r}\right)^2/\eta}$. With the equations above, we can express $W^{\text{in}}(0,0)$ and $W^{\text{out}}(0,0)$ the negativity values at the origin of phase space at the input and output of the teleporter. Furthermore, both Wigner function can be calculated exactely and used to predict the output of the teleporter. As expected for unity gain teleportation, the $W^{\text{out}}(0,0) = 0$ threshold is independant of s and can be expressed as a function of the two parameters η and r in our model by $r = \ln\sqrt{2/(2\eta-1)}$ at threshold. APD triggered non-Gaussian statse have been shown to have complex multimode properties. In the limit of small s and small R a simple multimode picture describes the input state as $e^{-\frac{s}{2}(\hat{A}^{\dagger 2} - \hat{A}^2)}\hat{A}^\dagger|0\rangle$ with the wave packet mode operator $\hat{A} = \int f(\omega)\hat{a}_\omega d\omega$, and $f(\omega)$ the bandwidth spectrum of the optical parametric oscillator used to produce the squeezed vacuum state $\hat{S}_s|0\rangle$. We investigate how this multimode aspect translates in term of teleportation and express in the Heisenberg picture the relation between input $(\hat{x}_{\text{in}}, \hat{p}_{\text{in}})$ and output $(\hat{x}_{\text{out}}, \hat{p}_{\text{out}})$ quadrature operators for unity gain teleportation. Thanks to this linear transformation and the linear model of input state in the Heisenberg picture, multimode teleportation reduces to monomode teleportation with an effective EPR parameter r_{eff} given by the relation $e^{-r_{\text{eff}}} = \int f(\omega) e^{-r(\omega)} d\omega$ where as a matter of fact $r(\omega)$ is the EPR correlation spectrum of the teleporter, with unit $20/\ln(10)$ dB. After we estimate precisely the relevant experimental parameters, we can now predict the shape of the input and output Wigner functions W^{in} and W^{out}. We find fidelities of 0.987 and 0.988 between the experimental and predicted Wigner functions for W^{in} and W^{out}. Furthermore, the predicted value of output negativity is $W^{\text{out}}(0,0) = -0.0243$, to compare with the experimental results -0.022 ± 0.003.

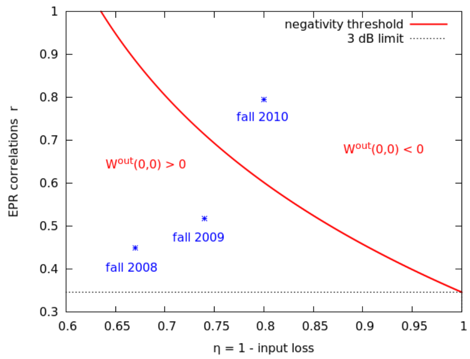

Figure 3: Threshold relation between EPR correlations r and input equivalent losses $1 - \eta$.

4. Conditional Teleportation

The continuous variable teleportation protocol as it was proposed in [17] is a deterministic protocol, which always succeeds but also always adds a minimal amount of noise to the output teleported state. We present and demonstrate how to experimentally implement conditional teleportation to further enhance teleportation of non-classical features of the Wigner function as was originally proposed in [21]. In the Kimble-Braunstein teleportation protocol [17], homodyne detection is used by Alice to perform joint quadrature measurements and can be used in principle for conditioning: only when Alice's quadrature measurement results meet chosen requisite conditions that teleportation will be considered successful as an operation on its own. The conditioning scheme is based on a threshold mechanism. If Alice measurement $\xi = (\bar{x}_u + i\bar{p}_v)/\sqrt{2}$ falls inside a circle of radius L, then the output teleported state is accepted. If not, the output teleported state is rejected. The conditioning algorithm exploits the fact that a smaller and smaller measured value of ξ on Alice side means smaller and smaller displacements on Bob side. In other words, if for instance $\xi = 0$, Bob does not need to perform any displacement and the output teleported state is naturally found to be identical to the input state. Experimentally, the output negativity $W(0,0|L)$ is estimated using the inverse Radon transform with the detection events satisfying the condition $\bar{x}_u^2 + \bar{p}_u^2 \leq 2L^2$ The evolution with the control parameter L of both the negativity $W(0,0|L)$ and the fraction of selected events can be evaluated for many values of L with the same experimental data set after the experimental measurement phase. Fig.4 shows experimental results of the probability of success $P(L)$ of conditional teleportation with the value of the parameter L and the evolution of $W(0,0|L)$ with the value of the parameter L. Conditional teleportation can be seen as an advanced technique of noise filtering where information at the output of the teleporter which is judged too noisy is progressively removed from the final experimental data set.

5. Conclusion

In Sec.2, we have demonstrated an experimental quantum teleporter able to teleport full wave-packets of light while at the same time preserving the quantum characteristic of strongly non-classical superposition states, manifested in the negativity of the Wigner function. This experiment thus constitutes an important breakthrough and opens the door to universal QIP and further hybridization schemes between discrete and continuous variables techniques [7]. In Sec.3, we have shown that a careful multimode model of both the non-classical input state and the broadband teleportation apparatus were necessary to understand the exact behavior of the experimental apparatus and predict precisely the value of the negativity and the shape of the Wigner function at the output of the teleporter. Our multimode models of non-classical wave-packet of light and broadband teleportation is precise enough to explain the measured experimental results. Finally in Sec.4, we have introduced the idea of Gaussian conditional

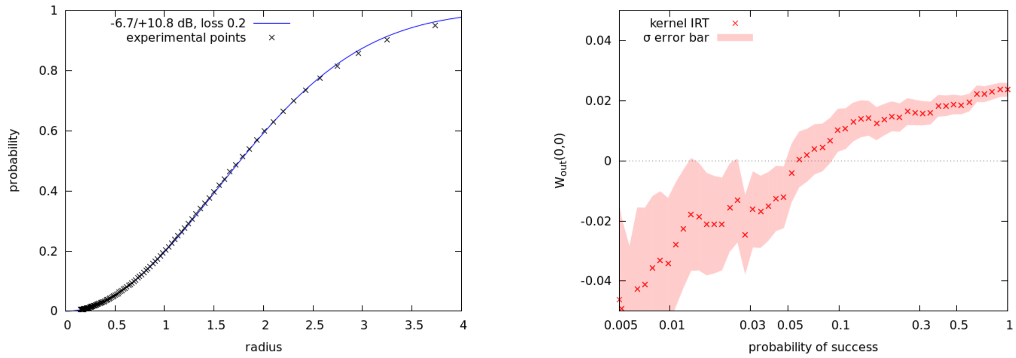

Figure 4: Left: probability of success of conditional teleportation, experimental results and theoretical prediction. Right: improvement of output Wigner function negativity W_{out} with conditional teleportation.

teleportation to balance a continuous variable teleportation apparatus between determinism and amount of errors. We have shown experimentally that a simple conditioning done with Alice's measurements can be used to increase the negativity and the purity of the output teleported quantum state.

6. References

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