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Quantum state reconstruction of an intense polarized optical beam via weak measurement

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ABSTRACT

An alternative experiment scheme of quantum state reconstruction is proposed for an intense polarized optical beam via weak measurement with common elements in laboratories. One of the main differences between our scheme and a previous one is that the homodyne detection of mode quadratures of the unpolarized beam outputs is replaced by inputting orthogonally polarized beams and measuring the polarization of the outputs. The approximated formulas are established to explain the relation between experiment data and the magnitude and phase of a pure state wave function at its quadrature eigenvalues. Some constructive suggestions for users are obtained from the simulation: First, the validating condition of our scheme is that the phase gradient of the state wave function must be continuous at the observable eigenvalues; Second, for more accurate and reliable results, we suggest selecting the initial meter state as a squeezed state, choosing the beam splitter reflectivity as small as possible, and collecting as much data as possible by extending the measurement time; Third, one should avoid the error of measurement basis phase rotation since when this error is higher than 0.2 rad, the fidelity is lower than 0.9, and prevent the error of device readout drift particularly on the meter beam since when this error on the meter beam is higher than 0.02 unit corresponding to the quadrature, the fidelity is lower than 0.9.

1. Introduction

A quantum state, which plays a fundamental role in all aspects of researches concerning physical quantum systems, enables an observer to make the best possible statistical predictions about interactions involving the system. Quantum state reconstruction is to recognize an unknown state based on as much available measured information as possible. Quantum state tomography (QST) is a useful tool to achieve state reconstruction [1,2]. Conventionally, QST exploits multiple projective measurements with different projection bases to collect data and can be used to reconstruct both pure and mixed state. However this approach requires a complete set of observable bases as projectors and a numerical search for a physically meaningful state is also needed over the alternatives consistent with the measured projective slices.

Alternatively, in 2011 Lundeen proposes an experimentally successful scheme [3] by using direct state measurement (DSM), *i.e.* using weak measurement to obtain the real and imaginary part of a quantum state with four steps: initial state

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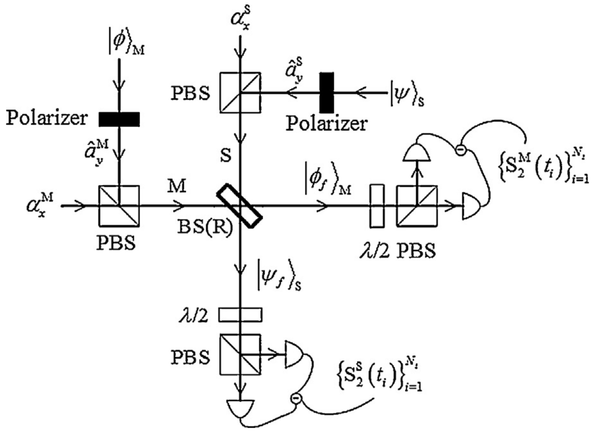

Fig. 1. The experiment configuration of the scheme. Initial inputs are generated by laser generators followed by some modulations, but here we neglect laser generators in this figure for simplicity. Beam S and beam M represent a signal beam and a meter beam respectively, BS(R) stands for a beam splitter with reflectivity R, PBS is a polarizing beam splitter, λ/2 represents a half-wave plate and other marks are explained in the text.

preparation, weak measurement, post selection and weak value readout. The review about weak value can be seen in Ref. [4]. Other applications of weak measurement are improving quantum discord [5], enhancing quantum entanglement [6], generating multi-photon entangled states [7], etc. Therefrom, researches on quantum state tomography via weak measurement emerge in large numbers. Some topics are precision metrology using weak measurement [8], direct measurement of a 27-dimensional orbital-angular-momentum state vector [9], a comparison between direct state measurement and tomography on state estimation [10], state tomography via weak measurements [11], phase estimation with weak measurement using a white light source [12], a quantum optical reconstruction scheme using weak values [13], a method to realize weak measurement of the arrival time of a single photon [14], etc.

Generally, a pure state $|\psi\rangle$ represented in a quadrature $\hat{X}$ picture is a wave function $\psi(X) = \langle X|\psi\rangle = |\psi(X)|e^{i\,\varphi(X)}$, thus values of magnitude $|\psi(X)|$ and phase $\varphi(X)$ at different eigenvalues of quadrature $\hat{X}$ are significant state-describing quantities. Specifically in DSM, post selection results and weak value readouts are recorded as data corresponding to these state-describing quantities. Unlike QST, these data are collected at a fixed projection direction, *i.e.* quadrature $\hat{X}$, and there is no need for a search algorithm, since the normalized reconstruction result is definitely physical. However, DSM is only suitable for pure state reconstruction.

A theoretical reconstruction scheme via DSM is proposed at Ref. [13], which uses a beam splitter to couple input beams and exploits homodyne detection to measure quadratures of optical modes. Empirically, operations such as phase modulation at local oscillators in homodyne detection are hard to perfectly perform, since practical errors cannot be completely avoided. Besides that, previous research papers seldom discuss about the quantum state reconstruction of an intense polarized optical beam via weak measurement.

In this paper, we propose an alternative experiment scheme for quantum state reconstruction via weak measurement. The quantum state is carried by an intense polarized optical beam. Instead of using homodyne detection with a local oscillator at the unpolarized beam output of a beam splitter, in our scheme the mode quadrature measurement is realized by inputting orthogonally polarized beams and measuring the polarization of the outputs. This is because the mode quadratures of a polarized intense beam can be reflected by the beam polarization operators, *i.e.* the Stokes parameter operators for the beam polarization. The scheme is demonstrated in detail and the approximated formulas are established to explain the relation between experiment data and the magnitude and phase of a pure state wave function at its quadrature eigenvalues. A comparison is made between this proposed scheme and an existing one. Some constructive suggestions for users are obtained from the simulation, including the validating condition of the scheme and the influence of experiment settings and errors on the result.

2. The reconstruction scheme

The scheme is that a signal beam with an unknown quantum state and a meter beam with a fixed initial state are coupled at a beam splitter, in which the two beams are both polarization modulated composite beams and the coupling strength of the beam splitter is weak, then experiment data are collected through measurement on observable polarization operators at the outputs of a beam splitter, at last the unknown state is reconstructed via statistical calculation from collected data. The experiment configuration is depicted in Fig. 1, with common optical elements in laboratories including laser generators, polarizers, beam splitters (BSs), half-wave plates, polarizing beam splitters (PBSs) and photodiodes. Functions and mathematical descriptions of these elements are given in detail in Ref. [15].

The collected data are polarization intensity of beam S and beam M, noted as $\{S_2^S(t_i)\}_{i=1}^{N_t}$ and $\{S_2^M(t_i)\}_{i=1}^{N_t}$ for N_t times of measurement. The polarization modulation is that a composite mode consists of two independent linear polarized modes,