Stimulated emission quantum state tomography for frequency non-degenerate entangled photon pairs

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Abstract: Frequency non-degenerate entangled photon pairs have been employed in quantum communication, imaging and sensing. In order to characterize quantum entangled state with long wavelength (infrared, IR or even terahertz) photon, one needs to either develop the single-photon detectors at the corresponding wavelengths or use novel tomography technique, which does not rely on single-photon detections, such as stimulated emission tomography (SET). Here we use a frequency non-degenerate polarization entangled photon source, generating one photon at 1550 nm and the other one at 810 nm. We use standard quantum state tomography and SET to measure the density matrix of photon pairs and obtain highly consistent results, showing the reliability of SET. Our work paves the way for efficient measurement of entangled photons with highly dissimilar frequencies, even to the frequencies where single-photon detections are not available.

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1. Introduction

Entanglement is the quintessential resource in emerging quantum technology such as quantum computation [1], quantum communication [2] and quantum metrology [3]. Charactering entangled state is a prerequisite for many quantum information tasks. For photonic system, quantum state tomography (QST) [4] can provide density matrix by using coincidence measurement with single-photon counting modules (SPCM). Silicon-based SPCM (Si-SPCM) have been widely used for detecting visible photons. Single-photon detector technology makes great improvements in recent years and extends the detection spectral range into near infrared (NIR) and IR regions [5]. For instance, one can use frequency up-conversion detector (FUCD) [6,7] and superconducting single-photon detectors (SSPDs). Although both offer excellent performance, extra assistant equipment is needed. For FUCD, an auxiliary pump laser and an extra nonlinear crystal are required to facilitate high-efficiency single-photon frequency conversion. For SSPD, it requires cryogenic operation environment. To develop a simpler detection scheme, particularly for entangled state characterization, is highly desirable.

Stimulated emission tomography (SET), proposed by Sipe et al. [8], is an alternative and reliable method to characterize quantum entangled state. It doesn't require single-photon counting and coincidence measurements comparing to standard QST. Stimulated emission in non-linear optics is realized by injecting particularly prepared seed light into a non-linear crystal. In [9], Fang et al. first experimentally demonstrated SET method by measuring the joint spectral density of entangled photon pairs, in which they used laser light and classical light detector. By employing carefully prepared seed light with different degrees of freedom, such as wavelength [9,10], polarization [11,12,13], and path [13], one can characterize different correlated/entangled states of photon pairs.

Most of previous experimental demonstrations of SET concentrate on entangled photon pairs with similar wavelengths. In this work, we investigate frequency non-degenerate polarization entangled state, consisting of one photon at 810 nm and another one at 1550 nm. Such entangled photon pairs have been used in practical entanglement-based quantum key
distribution experiments, which allows the 810 nm photon to be detected locally with a low-noise Si-SPCM at Alice’s node and the 1550 nm photon to be transmitted to Bob’s site via a low-loss optical fiber [14]. Frequency non-degenerate entangled photons have the application prospect in quantum imaging [15,16] and sensing [17,18]. Classical IR imaging/sensing technology has wide applications in material characterization, gas sensing, biological research. IR imaging technology with the help of quantum resource could bring revolutions in the field. Therefore, SET renders solutions for economical, rapid and detector availability issues.

2. Experiment

In our experiment, we prepare entangled state via type-I spontaneous parametric down-conversion (SPDC) process in non-linear crystal (NLC) 5% MgO:LiNbO3. A single-mode laser centered at 532 nm incident on NLC can generate a pair of correlated photons with central wavelength \( \lambda_s = 810 \) nm and \( \lambda_i = 1550 \) nm, i.e. \([532]_p \rightarrow [810]_s |1550]_i\), where indexes \( s \) and \( i \) denote signal and idler photons. The experimental setup, depicted in Fig. 1, is composed of three parts which are entangled state preparation, tomography and seed state preparation. The pump light with an average power of 50 mW is prepared in diagonal polarization. It is then separated by a beam displacer (BD-1) into horizontal polarized light in upper path and vertical polarized light in lower path which will be rotated to horizontal polarization by D-shaped half-wave plate (D-HWP). Horizontal polarized pump light in both arms is focused onto NLC, which has a thickness of 2 mm and its optics axes was cut at 68° to the surface for type-I SPDC phase matching condition. This process generates photon pairs both in vertical polarization direction. The signal and idler photon are separated by Dichroic Mirror (DM) into transmission and reflection directions, respectively. Correlated photon pair generated in lower path is rotated by a D-HWP to horizontal direction, i.e. the polarization state of correlated photon pairs is \([H]_s |H]_i \) and \([V]_s |V]_i\) in lower path and upper path respectively. The signal and idler photon generated in both arms are combined at the end of BD-2 and BD-3 separately, then the resultant state is \(1/\sqrt{2}([H]_s |H]_i + e^{i\theta}[V]_s |V]_i\) , where \( \theta \) is the relative phase of photons propagating along upper and lower path. The phase \( \theta \) can be adjusted via appropriate tilting of BD-2 and BD-3 in our experiment.

![Fig. 1. Schematic of experimental setup for stimulated emission tomography (SET). Three modules include (a) entangled state preparation, (b) seed state preparation and (c) tomography. Entangled state preparation module generates polarization entangled state of 810 nm and 1550 nm photons. The details can be found in the main text. Seed preparation module prepares seed light centered at 810 nm with different polarization states. Tomography module is used to measure down-converted photons for quantum state tomography. In SET, we only need detect stimulated generated 1550 nm light with a power meter (PM). BD: Beam Displacer; NLC: Non-linear Crystal; DM: Dichroic Mirror; HWP: Half Wave Plate; D-HWP: D-shaped Half Wave Plate; QWP: Quarter Wave Plate; PBS: Polarized Beam Splitter.](image-url)
The nonlinear optical process facilitates SET is different frequency generation (DFG), which obey to phase matching and energy conservation conditions, similar as those in SPDC. By injecting seed light (~810 nm), the stimulated generated light (~1550 nm) can be easily detected with power meter. As mentioned above, we use polarization entangled photon pairs. By properly setting the polarization of seed light, we can control the efficiency of DFG. Based on the measurement result of stimulated idler photon detection under different polarized seed light, we can analyze entangled state. In our experiment we use power meter for idler photons detection (1550 nm). Additionally, we also use Optical Spectrum Analyzer (OSA) to measure idler photons’ spectrum. Compared with QST employing high performance single-photon detectors, SET only requires visible light laser and classical infrared light detector, which are easier and faster to obtain. In SET approach, we set the seed light appropriately at 810 nm and incident onto the NLC to generate stimulated idler photons via DFG, which can be detected by classical intensity detector.

In order to obtain the density matrix with SET, different polarized states of the seed light are prepared in the seed state preparation module (Fig. 1b) from a continuous wave laser (SolsTis 3500 XL SRX, M SQUARED). Then they are sent into NLC, which allows idler photon generation via DFG. We prepare seed light in six different polarization states (i.e. $|H\rangle_s, |V\rangle_s, |D\rangle_s, |A\rangle_s, |R\rangle_s, |L\rangle_s$), and analyze the stimulated idler photon by single-photon quantum state tomography. This is equivalent to make coincidence measurements in 36 settings which can provide us full knowledge about density matrix of entangled state. For example, if we prepare seed state in horizontal polarization direction the maximum optical power could be measured in H basis, and minimum value measured in V basis.

Note that because we employ Type-I SPDC phase matching condition for both arms in NLC, i.e. $|H\rangle_p \rightarrow |V\rangle_s, |V\rangle_p$, we need rotate H polarization component of superposition seed states (i.e. $|D\rangle_s, |A\rangle_s, |R\rangle_s, |L\rangle_s$) into V to stimulate idler photon generation. Then the diagonal polarization state of the seed light, $1/\sqrt{2}(|H\rangle_s^{super} + |V\rangle_s^{lower} \rangle$, should be transformed into $1/\sqrt{2}(|V\rangle_s^{upper} + |V\rangle_s^{lower} \rangle$ by using D-HWP, which is a superposition state of vertical polarized state in upper arm and lower arm. The incident seed light intensity is about 20 mW with the central wavelength of $\lambda_s = 810$ nm. We obtained a stimulated idler output power is approximately 0.06 nW at the maximum.

3. Results

To benchmark the SET result, we first perform standard QST with coincidence measurements with single-photon detectors. By adjusting path delay of signal photon, the quantum state is close to the maximally entangled state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_s, |H\rangle_s + |V\rangle_s, |V\rangle_s).$$

We show the experimental raw coincidence counts in Fig. 2a. It is clear to see coincidence counts corresponding to HH, VV, DD, AA, RL and LR are at the maximum, and HV, VH, DA, AD, RR and LL are at the minimum. The other 24 coincidence counts are about half of the maximum. This is due to the symmetry of state $|\Psi\rangle$. In Fig. 2b, we show the real and imaginary parts of the reconstructed density matrix of $|\Psi\rangle$, from which we obtain the state fidelity of 96.660 ± 0.001%.

We then proceed to the results of SET. Note that before SET, we firstly adjust relative phase between H and V of seed states on NLC by reducing stimulated anti-diagonal polarized idler
output power to minimum via tilting BD4 when the incident seed light is in the diagonal polarization state. In Fig. 2c, we show a seemingly similar figure as Fig. 2a. However, in Fig. 2c, the x-axis and the y-axis correspond to the polarization orientations of seed light and the polarization analysis of the idler light, respectively. Via analyzing stimulated idler power raw data in Fig. 2c with the maximum likelihood technique, same as QST, we can construct density matrix shown in Fig. 2d, and obtain the fidelity of 99.381 ± 0.012%. Moreover, we also use an OSA to measure the power of idler along with its spectrum. The results are shown in Fig. 3, and we obtain the state fidelity of 99.575 ± 0.001%.

![Fig. 2. Quantum state tomography (QST) and stimulated emission tomography (SET) measurement results are shown in panel (a)-(b) and (c)-(d), respectively. (a): coincidence counts measured in all 36 measurement settings, which are measured with a Si Single-Photon Count Module for signal photon and a Superconducting Single-Photon Detector (SSPD) for idler photon with 25 seconds integration time. (b): polarization entangled state density matrix, left and right figure are real and imaginary part of density matrix constructed from the coincidence counts in (a). (c): stimulated idler photon power measured in all 36 measurement settings, which is collected by power meter. (d): polarization entangled state density matrix obtained from SET, left and right figure are real and imaginary part of density matrix constructed by stimulated idler photon power in (c).]
Fig. 3. Stimulated emission tomography (SET) measurement results measured by Optical Spectrum Analyzer. (a): stimulated idler photon power measured in 36 measurement settings. (b): polarization entangled state density matrix, left and right figure are real and imaginary part of density matrix constructed by stimulated idler photon measurement result above. Note that what we mean about HV setting in SET is that we send seed light with H polarization and detect stimulated idler in V polarization. Other settings follow the same rule.

Fig. 4. The joint spectral intensity profile of correlated photon pairs is shown in (b). The left figure (a) display spectral distribution of idler photon from SPDC. The right figure (c) show idler spectral distribution generated by stimulated process with narrow continuous seed light at the wavelength of $\lambda = 810$ nm in DFG. The figure (d) and (e) are stimulated idler spectral distribution measured by Optical Spectrum Analyzer in four measurement settings. Stimulated idler spectral distribution demonstrate above only include four measurement settings, and the stimulated idler power value shown in Fig. 3e is the maximum value of stimulated idler power measured by OSA in corresponding setting.

Although the density matrix of the polarization entangled state acquired by QST and SET are quite close, there exists a small discrepancy in the relative phase between $|H_i\rangle|H_i\rangle$ and $|V_i\rangle|V_i\rangle$. The value of $\theta$ inferred by QST is 0.0138, whereas the value evaluated by SET based on OSA and power meter measurement results is 0.0247 and 0.0252 respectively. The reasons of this small discrepancy ($\sim 0.01$) are that we have different spectral distributions for the idler photon’s collected in QST and SET. In QST, the measured phase between $|H_i\rangle|H_i\rangle$ and $|V_i\rangle|V_i\rangle$ is average over all spectrum that satisfy phase matching condition of SPDC. Note that in ref [11], this phase discrepancy is as large as 0.289, which is about 30 times larger than our
Another discrepancy of the results obtained from QST and SET is the state fidelity to Eq. (1). We obtain higher fidelities by using SET comparing with QST. This discrepancy could be explained from the frequency-polarization correlations [19]. In a typical SPDC source for generating polarization entangled photon pairs, photons’ polarization and frequency are correlated due to the phase matching condition and pump spectrum. In order to obtain high-quality polarization entangled states, one normally uses narrow-band interference filters to select partial bandwidth of the photons to approximate a single frequency mode [20]. By doing so, the frequency uncorrelated photon pairs will be closer to the maximally entangled states in polarization. Here we use a narrow-band seed light to stimulate the generations of idler photons. Therefore, idler photons generated via DFG, which fulfill the phase matching condition given by the narrow-band seed light, have significantly narrower bandwidth comparing to that generated via SPDC. This could be viewed as an active filtering process and hence the state fidelity to the maximally entangled state is higher in the case of SET. In Fig. 4b, we plot the calculated joint spectral intensity (JSI) profile of our SPDC process. The spectrums of idler photon generated from SPDC and DFG are shown in Fig. 4a and Fig. 4e, respectively. It is clear to see that the spectrum of SPDC is much wider than that of DFG. In the Fig. 4d and Fig. 4e, we show stimulated idler spectrum detected by OSA in four measurement settings. Limited by spectral resolution of OSA, the measured FWHM of stimulated idler spectrum is larger than theoretical prediction shown in Fig. 4e.

4. Conclusion

In this work, we demonstrate that SET method is reliable for entangled photon pairs with 740 nm wavelength separation, i.e. one photon in visible range (\(\lambda_v = 810\) nm) and the other one in near-infrared range (\(\lambda_i = 1550\) nm). Infrared spectral region possesses important applications in quantum technology, such as quantum communication, and remote sensing. We show that SET can be an alternative tomography method without using single-photon detector. Especially, employing SET is quite beneficial in non-degenerate entangled photon pairs tomography. We expect this method could be helpful to the unexplored spectral range in quantum technology, such as mid-infrared and far-infrared regions [17,21], or even tera-hertz spectral range [22].

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