Notes

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November 23, 2018

Chapter 1

Single-photon sources

1.1 Requirements

Scalable photonic quantum technologies require on-demand single-photon sources with simultaneously high levels of purity, indistinguishability, and efficiency.

1.1.1 Purity

The level of single-photon purity. It can be measured with the second-order correlation $g^2(0)$. The smaller the better.

$$g^{(2)}(\mathbf{r}_1, t_1; \mathbf{r}_2, t_2) = \frac{\langle E^*(\mathbf{r}_1, t_1) E^*(\mathbf{r}_2, t_2) E(\mathbf{r}_1, t_1) E(\mathbf{r}_2, t_2) \rangle}{\left\langle |E(\mathbf{r}_1, t_1)|^2 \right\rangle \left\langle |E(\mathbf{r}_2, t_2)|^2 \right\rangle}$$

1.1.2 Indistinguishability

The photons emitted in a short period of time should be quantum mechanically indistinguishable. It can be measured from HOM experiments(two photons transmit a 50:50 beamer splitter).

1.1.3 Efficiency

Extraction efficiency is important for the single-photon source to be applied in scalable photonic quantum technologies. It can be calculated by overall system efficiency with correcting for various efficiency of other devices in the system.

1.2 Solution

1.2.1 Search for the materials

InAs/GaAs,GaAs/$\mathrm{Al_{0.25}Ga_{0.75}As}$ quantum dots

1.2.2 Improve the methons

$$\begin{cases} \text{nonresonant excitation of a QD microcavity:} \\ \qquad \text{degrade the photon purity and indistinguishability} \\ \text{resonant excitation of a QD in a planar cavity:} \\ \qquad \text{limited the extraction efficiency} \end{cases}$$

⇒ s-shell pulsed resonant excitation of a Purcell-enhanced quantum dot-micropillar system

The basic way to find how to inprove is like this.

1. analyze and find the limitation;
2. compare and choose the limitation which is the most important and easy to solve;
3. analyze what have others done to solve this problem and come up with new solution;
4. try.

Take [HWG+] as an example.

First, find the limitation is the compatibly achieving near-unity system efficiency and photon indistinguishability.

Second, choose to increse the single photons efficiency and find the main overhead of the resonant excitation is suppression of the scattering from the excitation laser which has the same wavelength of the quantum dot single photons. The filter will reduce the system efficiency by at least 50%.

Third, find some people use orthogonal excitation and collection but it still sacrifices the efficiency by 50%.

Last, design the scheme and try.

1.3 Some terms

1.3.1 Purcell effect

The Purcell effect is the enhancement of a quantum system's spontaneous emission rate by its environment. In the 1940s Edward Mills Purcell discovered the enhancement of spontaneous emission rates of atoms when they are incorporated into a resonant cavity (the Purcell Effect). The magnitude of the enhancement is given by the Purcell factor

$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda_c}{n}\right)^3\left(\frac{Q}{V}\right) ,$$

where (λ_c/n) is the wavelength within the cavity material of refractive index n, and Q and V are the quality factor and mode volume of the cavity, respectively.

Chapter 2

Boson sampling

2.1 Task

n single photons are prepared in m optical modes. These are evolved via a passive linear optics network $\hat{U}$. Finally the output statistics are sampled via coincidence photodetection. The experiment is repeated many times, reconstructing the output distribution P_S .

2.2 Requirement

A quantum boson-sampling machine can be realized by sending n indistinguishable single photons through a passive m-mode (m > n) interferometer, and sampling from the probabilistic output distribution. However, the overall performance of previous proof-of-principle boson-sampling experiments was limited due to the lack of high-quality single-photon sources and low-loss multimode circuits. In addition, the boson-sampling rate was significantly reduced due to the coupling and propagation loss in the multimode photonic circuits. So to scale up the boson-sampling, it needs high-quality single-photon sources, low-loss multimode circuits and can use spatial or temporal multiplexing and scattershot boson sampling schemes. By the way it also needs efficient multiphoton source.

2.3 Improvement

2.3.1 Indistinguishable single photons

Three key features are simultaneously realized in the experiment using pulsed s-shell resonant excitation of a single self-assembled InAs/GaAs quantum dot embedded inside a micropillar cavity.

Thanks to the pulsed resonant excitation method that eliminates dephasings and time jitter 28 , we obtained long streams of near-transform-limited single photons that are sufficient for multiphoton experiments on a semiconductor chip for the first time.

A remaining challenge is to remove the cross-polarization in the confocal set-up (used to extinguish the laser background), which reduced the single-photon source efficiency by half. This have been solved in 'Polarized indistinguishable single photons from a quantum dot in an elliptical micropillar'.

2.3.2 Ultra-low-loss photonic circuit

A new circuit design. A 9 × 9 mode interferometer is constructed, using a bottom-up approach, from individual tiny trapezoids. The surfaces of the trapezoids are optically coated with polarization-dependent beam-splitting ratios.

2.3.3 Using different scheme

In the photonic experiments the major obstacle to scaling up is the unavoidable photon loss, which can happen in the source, interferometer, and detectors. However, boson sampling with a few photons lost can increase the sampling rate, and in the lossy scenario, the sampling rate can exponentially grow with k. This work([WLJ+18]) gives a result on a more realistic model that losses happen anywhere except the interferometer and theoretical and numerical evidence that, path-independent loss, wherever it happens, is equivalent to a uniform loss at the single-photon source.

2.4 misc

complexity The probability amplitude of each output outcome is proportional to the permanent of a corresponding n × n submatrix, which is strongly believed to be intractable because calculating the permanent is a so-called #P-complete problem. Note that, however, boson sampling is itself not a #P-complete problem.

about the count rate Considering the detector dead time, the actural count rate should be corrected.

$$f_{true} = \frac{1}{1/f_{observe} - t_{dead}}$$

similarity and distance quantified the match between these two sets of distributions using the measure of similarity, defined as $F = \sum_i \sqrt{p_i q_i}$, and the measure of distance, defined as $D = \frac{1}{2} \sum_i |p_i - q_i|$

some parameters Large Purcell enhancement can enhance the radiative rate. Large Q factor is helpful to suppress the phonon sidebands.

misc In lossy boson sampling, when the number of lost photons increases, the distribution will be closer to the uniform distribution.

Chapter 3

Quantum manipulation

3.1 Quantum teleportation

[WCS+15] extends Quantum teleportation to multiple degrees of freedom by developing a method to project and discriminate hyper-entangled Bell states by exploiting probabilistic quantum non-demolition measurement.

The process is like this(see fig3.1).

First, Alice and Bob share a hyper-entangled photon pair 2–3. Then photon 1 and 2 go through PBSs.After it, if photon can be found on both sides, photon 1 and 2 become state in the two-dimensional subspace spanned by$|\phi\rangle^{\pm} = (|0\rangle_1^s|0\rangle_2^s \pm |1\rangle_1^s|1\rangle_2^s)/\sqrt{2}$ for the degree of freedom of spin angular momentum(SAM). At both outputs of the PBS, there are two polarizers, projecting the two photons into the diagonal basis$(|0\rangle^s + |1\rangle^s)/\sqrt{2}$. It should be noted that the PBS is not OAM-preserving, because the reflection at the PBS flips the sign of the OAM qubit. The PBS and two polarizers select the four following states out of the total 16 hyper-entangled Bell states: $|\phi^+\rangle_{12}|\omega^-\rangle_{12}, |\phi^-\rangle_{12}|\omega^+\rangle_{12}, |\phi^-\rangle_{12}|\chi^+\rangle_{12}, |\phi^-\rangle_{12}|\chi^-\rangle_{12}$

Then use quantum teleportation for probabilistic quantum non-demolition (QND) dection to judge whether there is one and only one photon.

Last, perform BSM on the remaining OAM qubit. Only the asymmetric Bell state will lead to a coincidence detection where there is one and only one photon in each output.Therefore, the state $|\omega^-\rangle_{12}$ can be distinguished by a coincidence detection in separate outputs, and jv z i 12 can be discriminated by measuring two orthogonal OAMs in either output. In total, these two steps would allow an unambiguous discrimination of the two hyper-entangled Bell states $|\phi^+\rangle_{12}|\omega^-\rangle_{12}$ and $|\phi^-\rangle_{12}|\omega^+\rangle_{12}$.

The main sources of error include double pair emission, imperfection in the initial states, entanglement of photons 2–3 and 4–5, two-photon interference and OAM measurement.

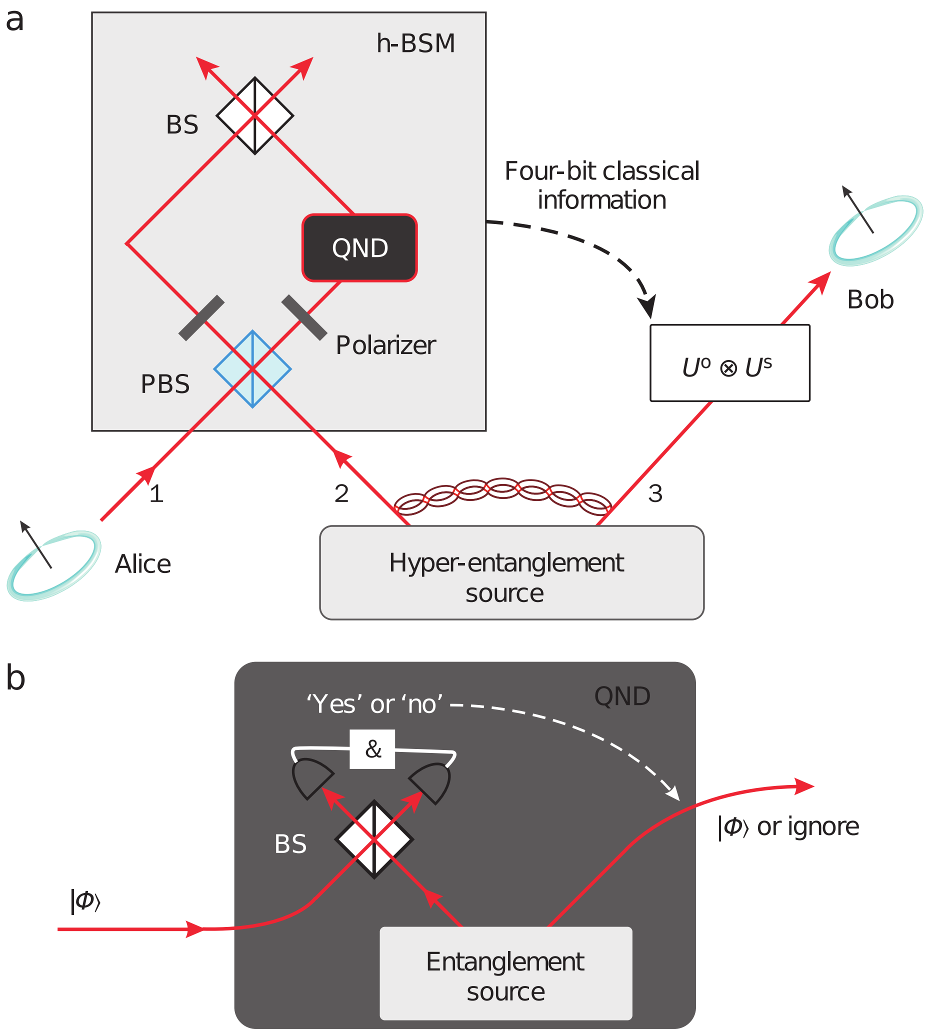

Figure 3.1: hyper Bell state measurement

3.2 Quantum entanglement

The main idea of generate entangled photons is like this.

First prepare n pairs of entangled photons $((|H\rangle|V\rangle - |V\rangle|H\rangle)/\sqrt{2})$ using spontaneous parametric down-conversion(SPDC) with a sandwichlike geometry where a half-wave plate (HWP) is sandwiched between two 2-mm-thick, identically cut BBOs. Then use PBS to select the signal photons with same polarization. If the n signal photons have same polarization, the $2n$ photons are entangled in $(|H\rangle^{\otimes n}|V\rangle^{\otimes n} - |V\rangle^{\otimes n}|H\rangle^{\otimes n})/\sqrt{2}$. If make idler photons go throuth halfwave plate, the $2n$ photons can be entangled in $(|H\rangle^{\otimes 2n} - |V\rangle^{\otimes 2n})/\sqrt{2}$. (I think so, but I don't know why there is no halfwave plate but it says they are in $(|H\rangle^{\otimes 6} - |V\rangle^{\otimes 6})/\sqrt{2}$ in [WLH+18]. Maybe it is just changing a denotation.)

To increase the number of entangled qubits, we can use more degrees of freedom. In [WLH+18], paths, polarization, and orbital angular momentum are used.

The process is like this. First produce polarization-entangled six-photon GHZ states in the way above. Then pass each single photon through a PBS which splits the photon into two paths denoted as up (U) and down (D) according to its polarization H and V, respectively. This process can be seen as a controlled-NOT (CNOT) gate where the polarization acts as the control qubit and the path acts as the target qubit, which transforms an arbitrary unknown input single photon in the state $\alpha|H\rangle + \beta|V\rangle$ to a polarization-path hyper-entangled state $\alpha|H\rangle|U\rangle + \beta|V\rangle|D\rangle$.Finally, we encode and entangle the OAM qubit to the photons. Inserting two spiral phase plates (SPPs) in both paths transforms the photon in the U and D paths into right-handed and left-handed OAM of $+\hbar$ and $-\hbar$ which we denote as $|R\rangle$ and $|L\rangle$, respectively. Each photon is thus prepared in a hyper-entangled state in the form of $\alpha|H\rangle|U\rangle|R\rangle + \beta|V\rangle|D\rangle|L\rangle$. By doing so, starting from the six-photon polarization-entangled GHZ state, we arrive at a hyper-entangled 18-qubit GHZ state in the form of $|\psi^{18}\rangle = (|0\rangle^{\otimes 18} - |1\rangle^{\otimes 18})/\sqrt{2}$ where for simplification we denote $|H\rangle, |U\rangle, |R\rangle$ as logic $|0\rangle$, and $|V\rangle, |D\rangle, |L\rangle$ as logic $|1\rangle$.

The next problem is to measure it and verify their multipartite full entanglement, which can be technologically more difficult than creating it. It is necessary to independently read out one DoF without disturbing any other. The measurements are designed sequentially in three steps.First, the spatial-mode qubit is measured using a closed or open Mach-Zehnder interferometer, with or without the second 50/50 beam splitter.The second step is to perform polarization measurement using a quarter-wave plate (QWP), a half-wave-plate (HWP) and a PBS.The last step is the readout of the OAM. I think this is the quintessence of this article. The method here is to deterministically map the OAM qubit to the polarization through two consecutive CNOT gates between the two DoFs that together form a quantum swap gate. This way changes a difficult task into a easier task.

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