Demonstration and Comparison of Different Entanglement Fabrication Approaches

Tianrui Che*

Department of Physics and Optoelectronic Engineering, Ocean University of China, Qingdao, China

*Corresponding author: ctr@stu.ouc.edu.cn

Abstract. Quantum entanglement is the most representative feature of quantum mechanics to classical mechanics. It is the delocalization, non-classical strong correlation among multiple quantum system. It has been developed for nearly one hundred years and a lot of methods of production and applications have been proposed. Aiming at the generation mode of quantum entanglement, this study presents two general preparation methods of quantum entanglement sources, including spontaneous parametric down-conversion (SPDC) and the preparation of quantum entanglement sources based on the four-wave mixing (FWM) effect. The principle, advantages and disadvantages of quantum entanglement sources are analyzed respectively. Finally, the research and application direction of the preparation method of quantum entanglement source are prospected. With the ability of preparation of quantum entanglement source, the application of quantum entanglement developed quickly, (e.g., quantum teleportation, entanglement swapping, quantum key distribution and quantum dense coding in the area of communication), and other area such as quantum computer, quantum imaging, quantum ranging and quantum clock synchronization. These results shed light on guiding further exploration of entanglement fabrication.

Keywords: Quantum entanglement; spontaneous parametric down conversion; four wave mixing effect; quantum dot.

1. Introduction

Quantum computing has great potential in the future. As a cutting-edge high-tech, it has become an emerging industry that the world's major companies are competing to enter. Google, IBM and Intel in the United States, Alibaba, Huawei, Tencent and Baidu in China, and Samsung, Airbus, Lockheed Martin and Fujitsu in the industry. Many countries and regions around the world have also issued a number of policies to support the research of quantum technology.

In 2020, IBM announced the development route of quantum computers in the next 10 years: it plans to build a medium-sized computer with 127 qubits in 2021, continue to break through and build 433 qubit computers in 2022, reach 1121 qubits in 2023, and the ultimate goal is to reach 1 million qubits [1].

As the core part of quantum information, high-quality quantum entanglement sources have also been vigorously developed. At present, there are several methods to prepare quantum entanglement sources: (1) Spontaneous parametric down conversion (SPDC) in nonlinear crystals; (2) Spontaneous four wave mixing (SFWM) of silicon-based materials or atomic ensemble; (3) Exciton processes in semiconductor materials such as quantum dots, nitrogen vacancy (NV) color centers.

Quantum entanglement sources prepared by different physical systems have their own advantages and disadvantages. In the future they can be organically combined to give play to their respective advantages and solve complex problems. Among many quantum light sources, SPDC has the longest history and the most mature technology.

In this paper, the research status and progress of the preparation methods of quantum entanglement sources are firstly reviewed, and the classification and comparison are made based on different generation mechanisms. The rest part of the paper is organized as follows. The Sec. 2 will analyze basic descriptions of quantum computing. The Sec. 3 will introduce common preparation methods of quantum entanglement sources, including the preparation of quantum entanglement sources based on spontaneous parametric down conversion (SPDC), four wave mixing effect (FWM). Subsequently, the limitation and outlook of quantum entanglement sources are prospected in Sec. 4. Eventually, a brief summary will be given in Sec. 5.

2. Basic descriptions of quantum computing

Primarily, it is necessary to do with the properties of the physical system and the manipulative ability of humans in order to realize the functions of quantum computing in a real physical system:

The basic unit of the system is a two-level quantum system (called qubit).

One needs to be able to prepare the initial state of the system, i.e., to zero each qubit;

Ability to perform arbitrary unitary operations on the system. Specifically, it is necessary to be able to perform any single-qubit unitary transformation on a single qubit, and to perform a controlled NOT gate operation on any two qubits (further theory shows that it can lead to quantum entanglement of two separable qubits).

To be able to carry out effective quantum measurements at the end state of the unified evolution of quantum computers.

The system must have a long coherence time, specifically, the system must be able to maintain the coherence during the unitary evolution and measurement stages.

The above requirements are proposed by IBM scientist DiVincenzo, known as the DiVincenzo criterion. In principle, any real quantum computer needs to meet this criterion. Similar to classical computers, input data and output data of quantum computers are both classical data. The difference lies in the way the data is processed, which is fundamentally different. A quantum computer prepares classical data in an initial quantum state, develops it into a final state through a series of unitary operations, performs quantum measurements on the final state, and outputs the result of the operation. The dotted box in Fig. 1 operates according to the laws of quantum mechanics.

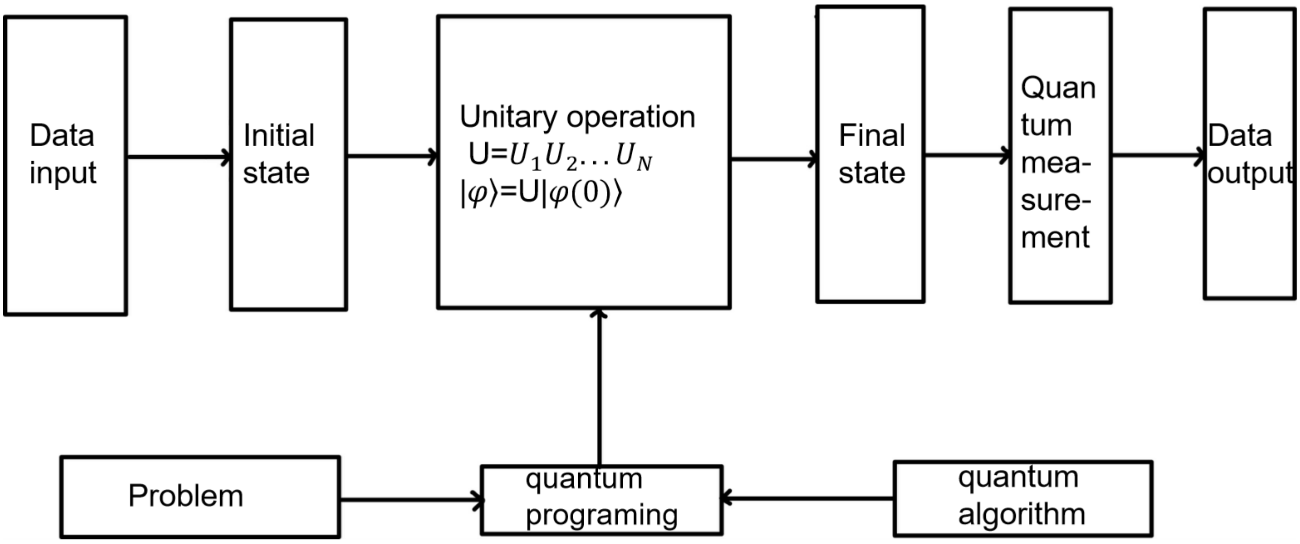

Fig. 1 Principles of quantum computer.

3. Common models

3.1. SPDC

SPDC uses the second-order nonlinear properties of nonlinear crystals to prepare quantum entanglement sources. According to the selection of nonlinear crystals, it can be divided into two methods: phase matching and quasi-phase matching (QPM).

3.1.1. Phase-matched preparation of quantum entanglement sources

SPDC is a nonlinear interaction process between the optical field and the crystal. After a pump light wave with a frequency of ω_p passes through the nonlinear optical medium, two other lights with lower frequency are generated under a certain probability, one of which is called the idler Light ω_i, the other light is called signal light ω_s. The SPDC process is the three-wave mixing process of the above three kinds of light in nonlinear crystals, which satisfies the conservation of energy and momentum, that is, the phase matching condition, which is expressed as: $\omega_p=\omega_i+\omega_s$ and $k_p=k_i+k_s$. Among them, k_p, k_i and k_s represent the wave vectors of pump light, idler light and signal light, respectively. Owing to the birefringence effect of the crystal, the refractive index of light in the crystal is also different. Therefore, it is necessary to select a suitable crystal as the conversion crystal to satisfy the phase matching, so as to realize SPDC. The general phase matching technique will choose BBO or potassium KDP crystal.

In 2020, Wang Dongyang et al. used two bonded BBO crystals with a thickness of 0.6 mm each to generate entangled two-photons with a purity of 97.25% [2]. In the same year, Qian Yuandong et al. studied the effect of temperature change on the output angle and conversion efficiency of SPDC-related photons [3], so as to obtain the suitable working temperature of the BBO nonlinear crystal, thereby reducing the influence of temperature on the long-term stability of the system. It is concluded that the appropriate temperature is 55℃ during the working process. LASOTA M et al. theoretically study the minimization of the temporal width of SPDC photons in the general case by exploiting variable parameters [4]. It has been demonstrated that adequate optimization of the SPDC is able to extend the maximum secure distance, which is about 30% higher than previous methods.

3.1.2. Preparation of quantum entanglement sources by QPM

In 1962, Armstrong J.A proposed the QPM technology, which provided a new research approach for SPDC [5], Although both QPM technology and phase matching technology use the second-order nonlinear effect characteristics of crystals, QPM periodically modulates the nonlinear polarizability, and uses spatial changes to compensate for the refractive index dispersion of the crystal.

The crystals that are generally selected for QPM are: PPLN、PPKTP、PPLT and PPRTA. In 2019, Wang Ye obtained an entangled source with a true coincidence-to-random ratio of 48.97 and a photon pair generation efficiency of 6.19×10^{-6}/pulse using a type ZPPLN ridge waveguide [6].

In the same year, Kim H et al. used picosecond pulses to pump PPLN to generate non-collinear SPDC and used a polarization-based Sagnac interferometer (as illustrated in Figure 2) to prepare a polarization-entangled photon pair light source in the 1550 nm communication band [7], whose visibility is greater than 96%. The CHSH-Bell parameter S was 2.72±0.04, with a violation of 18 standard deviations.

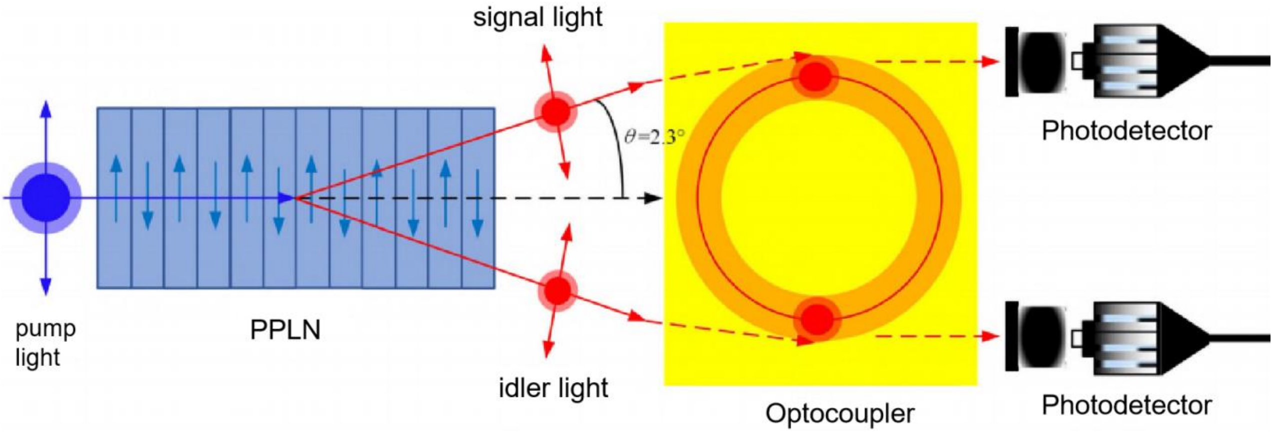

Fig. 2 Photon pairs are generated by QPM-SPDC.

3.2. FWM

FWM refers to the process of mutual modulation of 2 or 3 wavelengths of light in a nonlinear medium to generate 2 or 1 new wavelength of light. FWM depends on the third-order nonlinear properties of nonlinear media. For example, 2 pump photons of frequency ω_p will interact in a nonlinear medium due to their third-order nonlinear characteristics, resulting in an idler photon with a frequency ω_i shifted up compared to the pump light and a frequency ω_s compared with the pump light. There is an energy-time entanglement relationship between the signal photons and the idler photons.

In 2012, QIN Z et al. obtained -7 dB intensity difference compression at 8 kHz using a semiconductor laser to pump thermal Rb vapor [8]. In the same year, DING D S et al. fabricated a non-classically correlated two-colors photon pair using dual-wavelength ladder-type pumping thermal Rb vapor at 780 nm and 1529.4 nm [9], producing photon pairs at a rate of 10^7/s. In 2016, SHU C et al. generated sub-natural linewidth two-photons from a Doppler-extended thermal atomic vapor cell [10], and they used resonant SFWM to prepare double photons with controllable bandwidth and coherence time in a thermal paraffin-coated Rb vapor cell at 63 °C, which provides an idea for the research of miniature narrow-band two-photon sources. In 2019, LEE G H et al. demonstrated the non-local two-photons interference of energy-time entangled photon pairs through the Doppler-broadened SFWM process in stepped Rb atoms (as exhibited in Figure 3), with a visibility of 97.1± 2.5%, which is beneficial for long distance quantum communication [11].

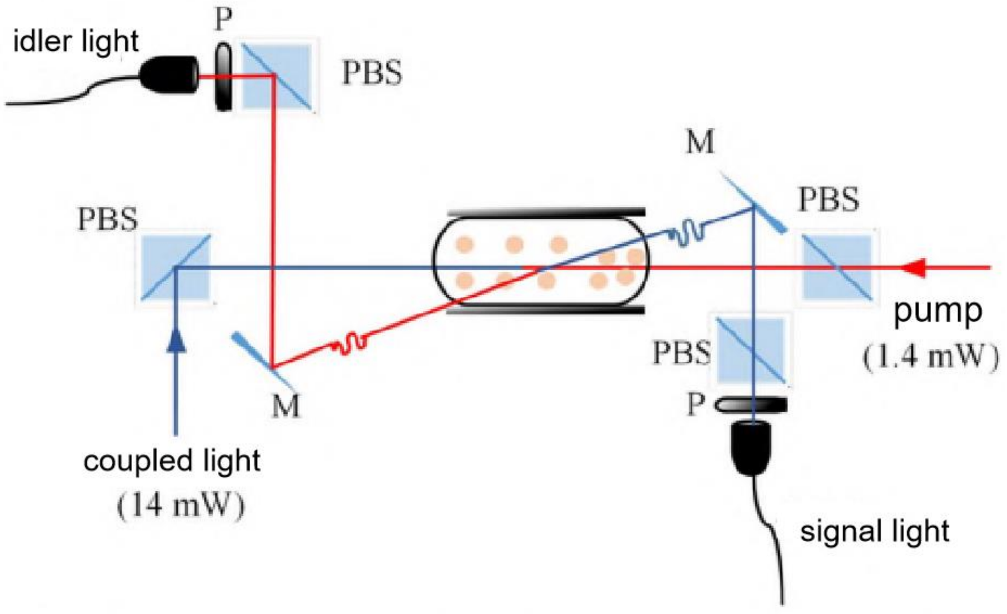

Fig. 3 Schematic diagram of the SFWM process

4. Limitation & future outlook

A major obstacle to the physical realization of quantum computers is the problem of decoherence. In theory, when one describes the qubit system that carries quantum computing, it is hoped that the system is closed and isolated from the interference of other environmental noises. The actual situation is that noise always exists in the physical control process or in the background environment.

Unruh found in 1995 that the existence of quantum noise will degenerate the quantum computing process into a classical probabilistic computing process, so that the advantages of quantum computing will no longer exist [12]. This is undoubtedly a disastrous result for quantum computing. However, based on quantum error-correcting codes, theories of fault-tolerant quantum computing have been developed. Quantum error correction codes have certain error tolerance thresholds, which are given by specific noise models and corresponding error correction coding methods.

If the quantum noise is below a given threshold, the quantum computation can be performed safely and the effect of the noise on the computation can be ignored. The theoretical study of fault-tolerant quantum computing using quantum error-correcting codes has become one of the most important topics in quantum computing theory research in recent years. Due to the particularity of quantum information, people have also discovered some unique mechanisms for avoiding the influence of noise, such as quantum error-avoiding codes, for special noise models, quantum Information can be encoded in a special code space, and noise has no effect on the state in this space [13]. There is also a method called the dynamic decoupling method, which eliminates the influence of the noise environment by means of dynamic control [14]. The above types of methods (especially quantum error correction codes) are proposed, so that the quantum computing process no longer has essential difficulties in principle.

The sources of quantum entanglement can not only be applied to quantum teleportation, quantum secure communication and quantum dense coding, but also can be applied to quantum precision measurement because of the high correlation between the two beams of light (idler light and signal light). In the future, it is expected to develop a quantum entanglement source with higher integration and better stability for quantum precision measurement in the microscopic world. Contemporarily, quantum technology is developing rapidly, especially in the field of information. With the proposal of the silicon-based entanglement scheme, quantum integration becomes possible. In addition, quantum computers will also be born with quantum integration. With the development of techniques and fabrication schemes, the application of quantum will not only be in the laboratory, but also in social life. Just like the development of electrons, quantum will also bring a different experience to our life.

5. Conclusion

In summary, this paper investigates different quantum entanglement sources based on various approaches. There are many methods for preparing entanglement sources, but the most common and mature solutions are SPDC. According to the selection of nonlinear crystals, it can be divided into two methods: phase matching and quasi-phase matching. It is widely used in various fields of quantum information, e.g., quantum key distribution, quantum teleportation, quantum computing, quantum simulation. According to the analysis, SPDC uses the second-order nonlinear properties of nonlinear crystals to prepare quantum entanglement sources. In addition, FWM refers to the process of mutual modulation of 2 or 3 wavelengths of light in a nonlinear medium to generate 2 or 1 new wavelength of light. Quantum entanglement sources prepared by different physical systems have their own advantages and disadvantages. In the future they can be organically combined to give play to their respective advantages and solve complex problems. Overall, these results offer a guideline for entanglement fabrication based on the state-of-art facilities.

References

[1] IBM’s roadmap for scaling quantum technology, 2020-9-16. Retrieved from https://research.ibm.com/blog/ibm-quantum-roadmap

[2] Wang Dongyang, Wu Junjie, Liu Yingwen, et al. Performance model and experimental implementation of entangled photon source. Computer engineering and science, 2020, 42(10): 1757-1764.

[3] Qian Y, Xia M, Li J, et al. Effects of temperature on downside parameter transforming energy output angle and efficiency. Acta of Photonics, 2020, 49(10): 206-215.

[4] Lasota M, Kolenderski P. Optimal photon pairs for quantum communication protocols. [2021 -01 -21]. Retrieved from: https://www.nature.com/articles/s41598-020-77662-2.

[5] ARMSTRONG J A. Interactions between light waves in a nonlinear dielectric. Phys Rev, 1962, 127: 1918-1939.

[6] Wang Ye. Polarization entangled light source based on nonlinear waveguide. Harbin: Harbin Institute of Technology, 2019.

[7] KIM H, KWON O, MOON H S. Pulsed Sagnac source of polarization-entangled photon pairs in telecommunication band. Scientific Reports, 2019, 9(1): 5031-1-5031-7.

[8] Qin Z, Jing J, Zhou J, et al. Compact diode-laser-pumped quantum light source based on four-wave mixing in hot rubidium vapor. Optics Letters, 2012, 37(15): 3141-3143.

[9] Ding D S, Zhou Z Y, Shi B S, et al. Generation of non-classical correlated photon pairs via a ladder-type atomic configuration: theory and experiment. Optics Express, 2012, 20(10): 11433-11444.

[10] Shu C, Chen P, Chow T K A, et al. Subnatural-linewidth biphotons from a doppler-broadened hot atomic vapor cell. Nature Communication. 2016(7): 12783-1-12783-5.

[11] Lee G H, Ihn Y S, Lee A, et al. Nonlocal two-photon interference of energy-time entangled photon pairs generated in Doppler-broadened ladder-type Rb 87 atoms. Physical Review A, 2019, 100 (5): 053817-1-053817-4.

[12] Unruh W G. Maintaining coherence in quantum computers. Physical Review A, 1995, 51(2): 992.

[13] Duan L M, Guo G C. Probabilistic cloning and identification of linearly independent quantum states. Physical review letters, 1998, 80(22): 4999.

[14] Viola L and Lloyd S. Phys. Rev. A 1998, 58: 2733-2744;