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Experimental investigation of the influence of laser intensity on the quality of Einstein-Podolsky-Rosen entangled photons*

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Using spontaneous parametric down conversion, polarization post selection and coincidence counting technique, the polarization Einstein-Podolsky-Rosen (EPR) entangled states are prepared. Experimental studies on the efficiency, contrast and fidelity with different pump laser intensities are performed systematically. The results show that the pump laser intensity distinctly influences the quality of entangled photons, especially the contrast and the fidelity. On the other hand, the pump efficiency of entangled photons is almost invariable, namely the entangled source brightness increases linearly with the increase of pump laser power.

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Quantum entanglement is the key resource of quantum information processing[1]. It is the basic feature of quantum mechanical principle different from the previous principle of classical physics[2]. Entangled photons are the core resource of quantum teleportation, quantum computing and quantum key distribution[3]. Many important experiments, such as quantum entanglement swapping[4,5], entanglement purification[6,7] and controllable quantum bit gate[8,9], can be realized using the polarization entangled photons. Due to the advantages of little coupling with environment, high transmission speed and simple generation, entangled photons become the main vehicle of quantum communication channel[10]. The entangled light source quality, such as brightness and fidelity, determines the communication speed, the channel capacity and the safety of long-distance quantum communication system[11]. So the preparation of high quality entangled states has been widely researched experimentally.

Using the parametric down-conversion principle, coincidence counting technique and polarization post selection, people have put forward many valuable technical schemes to prepare entangled photons[12-14]. In these schemes, the preparation of two-photon Einstein-Podolsky-Rosen (EPR) entangled state is the foundation. Although the parametric conversion technique has been applied to the preparation of entangled photons for many years, the investigation of the effect of laser intensity on the quality of entangled photons has not been reported. In this paper, we systematically study the effect of pump laser power on efficiency, contrast and fidelity of EPR entangled photons in parametric down-conversion process.

We use the parametric down-conversion scheme to generate the EPR entangled photon pair[15]. Then by the method of post selection and coincidence counting, we prepare the two-photon polarization entangled state. The schematic diagram of experimental system is shown in Fig.1.

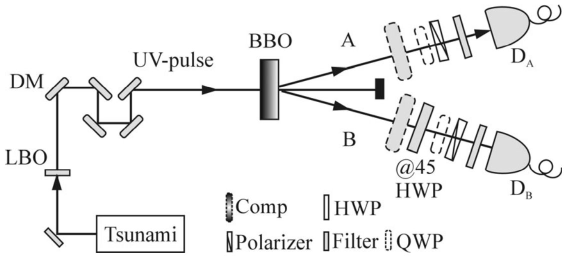

Fig.1 Schematic diagram of experimental setup for preparing polarization EPR entangled state

A light pulse from a mode-locked Ti: sapphire laser

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with the duration of 100 fs, the repetition rate of 80 MHz, the power of 1 W and the central wavelength of 780 nm first passes through a frequency doubler, that is, the LiB_3O_5 (LBO) crystal, and then is converted to an ultraviolet (UV) light pulse with the central wavelength of 390 nm. Through finely adjusting the focusing lens in front of the LBO crystal, the largest power of UV light can reach 350 mW. Then the UV light pulse passes through five dichroic mirrors (DMs) which are used to separate the mixed infrared and UV light components. Behind the five DMs, the UV light is focused on a β-barium borate (BBO) crystal. With appropriate cutting angle of BBO crystal and direction of pump laser, the II-type parametric down-conversion process is produced. In this process, the parameter down conversion of the 390 nm UV pulse occurs with a certain probability, and one photon is split into two photons with the orthogonal polarization directions, i.e., a 390 nm photon is split into two 780 nm photons. This process must meet energy conservation and phase matching. The principle of the II-type parametric down conversion is shown in Fig.2.

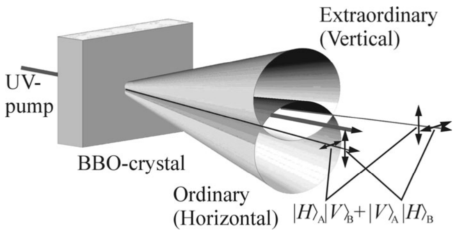

Fig.2 Principle of the II-type parametric down conversion

Due to energy conservation and momentum conservation, two frequency down-conversion photons are symmetrical. One photo appears in the extraordinary light cone above with vertical (V) polarization direction. Another photon appears in the ordinary light cone below with horizontal (H) polarization direction. According to the principle of quantum mechanics, the photons A and B appearing in the lines of two crossed light cones are indistinguishable. The state of photons A and B is $(|H\rangle_A|H\rangle_B+e^{i\delta}|V\rangle_A|V\rangle_B)/\sqrt{2}$. After polarization rotation and phase compensation, we can get the entangled state of two photons as

$$|\psi\rangle_{AB}=\frac{1}{\sqrt{2}}(|H\rangle_A|H\rangle_B+|V\rangle_A|V\rangle_B)\,. \tag{1}$$

Theoretically, the coincidence counting of two detectors only exists at states of $|H\rangle_A|H\rangle_B$ and $|V\rangle_A|V\rangle_B$. However, due to the double-pair effect of nonlinear process, stray light noise and electronic noise, the actual state becomes

$$|\phi\rangle_{AB}=|H\rangle_A|H\rangle_B+|V\rangle_A|V\rangle_B+|H\rangle_A|V\rangle_B+|V\rangle_A|H\rangle_B\,, \tag{2}$$

where $|\phi\rangle_{AB}$ is a mixed state. In theory, the states $|H\rangle_A|V\rangle_B$ and $|V\rangle_A|H\rangle_B$ of detectors A and B can not be $|H\rangle$ and $|V\rangle$ synchronously. But because of the influence of the noise, detector will detect small coincidence counting values of $N_{|H\rangle_A|V\rangle_B}$ and $N_{|V\rangle_A|H\rangle_B}$. Similarly, in +/− base, the coincidence counting values of $N_{|+\rangle_A|+\rangle_B}$ and $N_{|-\rangle_A|-\rangle_B}$ are large numbers, while $N_{|+\rangle_A|-\rangle_B}$ and $N_{|-\rangle_A|+\rangle_B}$ are small numbers. Here N is the coincidence counting of the detector. The contrasts on H/V base and +/− base are defined as

$$C_{HV}=\frac{N_{|H\rangle_A|H\rangle_B}+N_{|V\rangle_A|V\rangle_B}}{N_{|H\rangle_A|V\rangle_B}+N_{|V\rangle_A|H\rangle_B}}\,, \tag{3}$$

$$C_{+-}=\frac{N_{|+\rangle_A|+\rangle_B}+N_{|-\rangle_A|-\rangle_B}}{N_{|+\rangle_A|-\rangle_B}+N_{|-\rangle_A|+\rangle_B}}\,, \tag{4}$$

where the contrast is the ratio of the desired components to the other undesired ones. At the same time, the fidelities on H/V base and +/− base are defined as

$$F_{HV}=\frac{N_{|H\rangle_A|H\rangle_B}+N_{|V\rangle_A|V\rangle_B}}{N_{|H\rangle_A|H\rangle_B}+N_{|V\rangle_A|V\rangle_B}+N_{|H\rangle_A|V\rangle_B}+N_{|V\rangle_A|H\rangle_B}}\,, \tag{5}$$

$$F_{+-}=\frac{N_{|+\rangle_A|+\rangle_B}+N_{|-\rangle_A|-\rangle_B}}{N_{|+\rangle_A|+\rangle_B}+N_{|-\rangle_A|-\rangle_B}+N_{|+\rangle_A|-\rangle_B}+N_{|-\rangle_A|+\rangle_B}}\,, \tag{6}$$

where the fidelity shows the degree of the experimental state close to pure state.

In addition, the weighted total sum of each detector is defined as N_{tot}. Using the effective coincidence counting in H/V base and +/− base and the total sum, we can define the efficiency of producing EPR pairs as

$$\eta_{HV}=\frac{C_{|H\rangle_A|H\rangle_B}+C_{|V\rangle_A|V\rangle_B}}{N_{tot}}\times100\%\,, \tag{7}$$

$$\eta_{+-}=\frac{C_{|+\rangle_A|+\rangle_B}+C_{|-\rangle_A|-\rangle_B}}{N_{tot}}\times100\%\,. \tag{8}$$

We change the UV laser pump power by changing the semiconductor laser power. Using high efficient single photon detector and coincidence counting technique, the relations between UV laser power and generation efficiency, contrast and fidelity of the entangled photons are studied. The measurement data are shown in Tab.1. The results show that the single photon total count and the effective coincidence counting both increase with the increase of pump power. Namely, the brightness of entangled source increases with the increase of UV laser power.

Tab.1 Coincidence counting of entangled pairs with different pump powers

P (mW)	N_{tot}	N_{HV}	N_{VH}	N_{HH}	N_{VV}	N_{+-}	N_{-+}	N_{++}	N_{--}
50	86 041	58	62	10 188	10 468	181	170	9 900	10 141
100	179 867	132	140	21 120	21 000	382	384	20 306	20 292
150	261 834	204	322	31 297	30 902	648	648	30 466	29 906
200	382 841	336	648	44 248	45 395	1 026	1 081	43 002	43 188
250	456 438	440	888	53 078	52 495	1 318	1 398	50 692	52 106
300	531 901	606	1 302	60 980	62 734	1 786	1 717	59 730	60 562
350	579 298	737	1 549	66 506	68 882	1 943	2 024	65 729	69 289

According to data in Tab.1, the efficiency of entangled photons can be calculated as shown in Fig.3. The data show that the efficiencies of entangled photons for η_{HV} and η_{+-} are almost constant with different pump powers. So a brighter entangled source can be generated by increasing the UV laser power within limits.

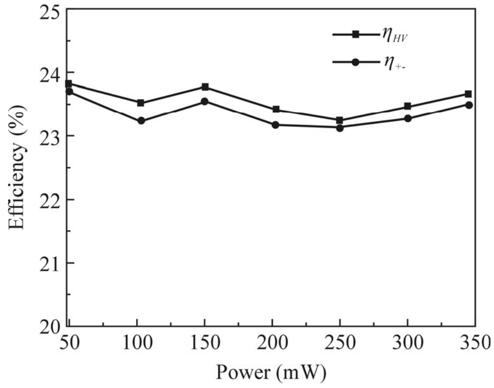

Fig.3 Efficiencies of entangled photons with different pump powers

The contrast and the fidelity versus pump power are shown in Figs.4 and 5, respectively. The contrast and the fidelity of entangled photons both decrease with increasing pump laser power. With the increase of laser intensity, the power density increases. The probability of double-pair effect increases with increasing the power density on crystal BBO. A pair of HV photons and a pair of VH photons are produced at the same time. Though the total photons of parametric conversion increase, the effective coincidence counting of post selection process reduces. It is because the double-pair effect decreases the contrast and the fidelity of entangled photons in the post selection process.

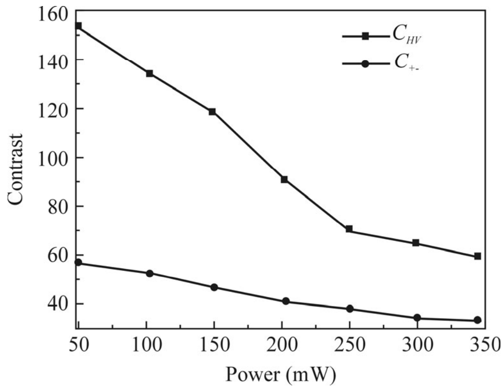

Fig.4 Contrasts of entangled photons with different pump powers

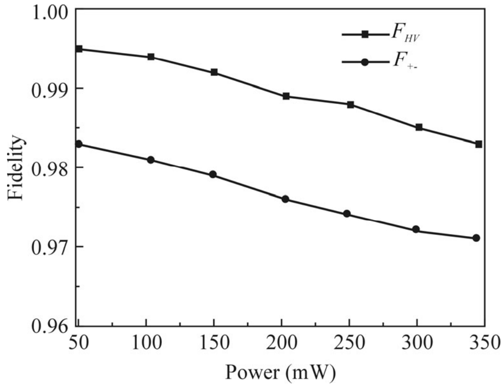

Fig.5 Fidelities of entangled photons with different pump powers

In summary, we generate the polarization EPR entangled states by the method of spontaneous parametric down conversion, polarization post selection and the coincidence counting technique. By changing the average power of mode-locked laser, the relations between efficiency, contrast and fidelity and pump laser intensity are investigated systematically. The results show that the pump laser intensity affects the quality of entangled photons, especially contrast and fidelity. On the other hand, the generation efficiency of entangled photons is almost invariable, namely the entangled source brightness increases linearly with the increase of pump laser power.

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