Manipulation of the spontaneous parametric down-conversion process in space and frequency domains via wavefront shaping

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The spontaneous parametric down-conversion (SPDC) source of entangled-photon pairs is important for applications in the quantum information process and quantum communication, but suffers from scattering by sample defect and air impurity. Here, we proposed an alternative scheme to manipulate the scattered SPDC process, where only a spatial light modulator was used to control the incident wavefront. The scheme was experimentally tested and also applied on the manipulation of photon pairs through the SPDC process with spectral control. This work proved the feasibility of manipulating nonlinear signals at quantum level with feedback-based wavefront shaping and also indicated applications in long-distance quantum key distribution, quantum communications, and quantum imaging, especially in complex environments.

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Entanglement is the main resource for many applications of quantum information processing, including quantum key distribution (QKD) [1–3], quantum teleportation [4,5], and quantum imaging [6]. The standard source of entangled-photon pairs is nowadays the nonlinear optical process of spontaneous parametric down-conversion (SPDC) in optics. SPDC sources of entangled-photon pairs of high quality and brightness can be routinely realized using various methods in nonlinear bulk crystal, waveguide crystal, and optical fiber [7–11]. In reality, photon pair generation and propagation with long distance in free space will be scattered by sample defect and air impurity, which influences the efficiency of propagation and even the rate of reception [12]. Hence, an appropriate way to restore the SPDC process is desired.
where $\alpha$ was a pulse laser with the center wavelength at 1556 nm, under the setup as shown in Fig. 2(a). The pump light source selected wavelength optimized by FBWS, which lead to a coherent superposition of the integration of all SLM segments. The spectrum is given by target at the wavelength of $\lambda$.

Pairs of single photons in our experiment were generated under the setup as shown in Fig. 2(a). The pump light source was a pulse laser with the center wavelength at 1556 nm, a pulse width of 1.0 ns, and repetition rate of 10 MHz. It was amplified by an erbium-doped fiber amplifier and converted via second-harmonic generation (SHG) in a PPLN waveguide. A polarization controller was used to ensure the high efficiency of SHG. The emitted laser centered at 778 nm was then used to pump the PPLN bulk to generate photon pairs. Here, two collimator fibers (CF1 and CF2) with high transmission at 780 nm and 1560 nm, respectively, were applied. A half-wave plate was used after the pump for polarization control because of the response characteristics of the SLM. Lens 1 and lens 2 were used as the expanding system in order to pump more SLM area, which was composed of $192 \times 1080$ pixels, each with a rectangular area of 8 $\mu$m $\times$ 8 $\mu$m. The SLM, lens 3, lens 4, and lens 5 formed a 4$f$-optical imaging system. Our experiment, the nonlinear crystal to generate collinear photon pairs is a type-0 PPLN bulk, 1 cm in length. A filter was then used to reject the pump laser.

The detector setups for scattering compensation and SPDC spectral control are shown in Figs. 2(b) and 2(c), respectively. The SPDC photons were separated by a 50:50 single-mode fiber beam splitter (BS) or filtered by different channels of the coarse wavelength division multiplexing (CWDM). The single-photon counting module (SPCM) ($10 \pm 0.2\%$ quantum efficiencies and about 100 dark counts) was applied to count photon pairs. SPCM1 was extern-triggered by SPCM2, in order to obtain the heralding efficiency ($H$) by measuring the conditional detection efficiency ($\eta_D$) of heralded photons [26, 27]. $\eta_D$ was defined as the coincidence counting rate ($R_C$) divided by the trigger photon detection rate ($R$), such that

$$\eta_D = R_C/R.$$  

$H$ was corrected by considering transmittances of all optical elements ($\eta$) shown as

$$H = \frac{\eta_D}{\eta},$$

where $\eta$ included SPCM1 and 2 quantum efficiencies of 10%, the influence of BS, estimated 4% reflection loss upon CF1 into free space, 5% loss due to the antireflection-coated surfaces of the five lenses, and the filter transmission of 95% at 1560 nm. Then two output ports of SPCM 1 and 2 were both connected to a time-to-digital converter (TDC) to measure the coincidence count in Fig. 2(b). All SLM and SPCMs were connected to a computer with a genetic algorithm (GA) for optimization. Here, $H$ served as the feedback signal, and GA was selected in the optimization process because it worked better in noisy environments [26]. All SLM pixels were regrouped and subdivided into $32 \times 18$ phase segments (N) for a faster optimization speed.

The temperature of PPLN was adjusted at $320 \pm 0.1$ K in order to meet the quasi-phase matching (QPM) condition. The CF2 was adjusted to get the maximum SPCM count. First of all, scattering media were not added, and the detector setup in Fig. 2(b) was applied. A typical compensation result of the domain structure’s scattering effect is shown in Fig. 3. The heralding efficiency $H$ increased with the iteration as expected and eventually reached a stable value. After 30 iterations, maximum $H$ arrived at 41.9% [Fig. 3(a)]. In other words, when a signal photon is detected by an SPCM, the probability of its twin idler photon being present is 41.9% [27]. $H$ was improved by 26.6% because the structure defect of PPLN was partly compensated by the optimization process. The final $H$ was
determined by the scattering strength of the PPLN domain structure and the number of defects in the crystal itself. It also depended on some details of GA, such as the segment size and mutation probability [28]. There are also many other optimization algorithms valid for the procedure, such as the continuous sequential algorithm, transmission matrix, and ant colony optimization. Each optimization algorithm has its exclusive characteristics but may not be well suited for noisy environments [28–30]. GA has its particular advantages in low signal-to-noise environment, and the convergence is fast, so it was chosen to do the optimization.

In traditional quantum researches, the coincidence count and the ratio of coincidences to accidental (CAR) were usually used to describe the entangled-photon pairs quality. Coincidences per pulse generated through SPCD can be expressed as

\[ C = \mu \eta_s \eta_i, \]

where \( \mu \) is the number of pairs generated per pulse, \( \eta_s \) and \( \eta_i \) are the overall collection efficiencies for the signal and idler photons, respectively [31]. CAR was calculated by taking the ratio of coincidences to accidentals such that

\[ \text{CAR} = \frac{C}{\left[ (\mu \eta_s + d_s)(\mu \eta_i + d_i) \right]}, \]

where \( d_s \) and \( d_i \) are the dark counts in the signal and idler detectors, respectively. In our experiment, \( d_s \) compared to \( \mu \eta_s \) or \( d_i \) compared to \( \mu \eta_i \) is small enough. So, we can substitute \( C \) in the denominator to obtain an equation that is dependent only on \( \mu \), which is

\[ \text{CAR} = \frac{1}{\mu}. \]

In our experimental setup, the coincidence events were averaged five times every 60 s during each iteration. As shown in Fig. 3(b), the coincidence count \( C \) increased, and the CAR decreased (\( \mu \) increased) with the iteration increasing, which proved the entangled-photon pairs were indeed increasing under the optimization. At the same time, the multiphoton effect was stronger because \( \mu \) increased, which showed the noisy environments. In Eq. (2), \( \eta_s \) and \( \eta_i \) were regarded as equal in estimation, which includes the collection efficiency and quantum efficiencies of SPCM in our experiment. The heralding efficiency \( H \) is identical to the collection efficiency. The increase of \( H \) and the decrease of CAR demonstrated that the FBWS optimization not only compensated for the scattering due to defects in PPLN but also increased collection efficiency.

Second, a scattering medium was added behind PPLN to simulate the air impurity that photon pairs propagating with long distance in free space would encounter [Fig. 2(a)]. In our experimental design, the scattering medium was some TiO\(_2\) nanoparticles deposited on an indium-tin oxide coated glass substrate by an electrophoresis method [32]. The detector setup is shown in Fig. 2(b). The initial value of \( H \) was 38.7%, and it was down by 50.9% after adding the scattering medium. During a similar optimization, it was increasing with the iteration as expected, and the saturated value was 36.0% after 250 iterations [Fig. 4(a)]. That means the scattering effect by the turbid medium has been compensated by 94.6%. During optimization, the coincidence events and CAR of each generation were also measured and are presented in Fig. 4(b), showing a conclusion similar to the above. The optimization needs more time (iterations) to achieve saturation. \( H \) was lower but improved by 92.7% because of the stronger scattering effect. Generally speaking, our scheme is more efficient, especially for an extra scattering medium or samples with defects. What is more, focusing and quantum imaging could be expected with an electron multiplying charge-coupled device or other quantum detectors.

Furthermore, manipulation of the SPDC process with spectral control was realized, indicating possible applications of long-distance quantum communication in complex environments. The experimental setup is illustrated in Figs. 2(a) and 2(c). The SPDC photons with 70 nm bandwidth (from 1530 nm to 1600 nm [33]) were divided by the CWDM with 13 nm bandwidth in each channel. As the theory in Eq. (1), any channel could be chosen to be enhanced by FBWS. For example, signals and idlers in different channels with central wavelengths of 1550 nm and 1570 nm were detected by SPCM1 and SPCM2, respectively. SPCM1 was extern-triggered by SPCM2, in order to obtain \( H \). Then \( H \) of frequency-conjugate pairs was regarded as the feedback for optimization. The initial value of \( H \) was about 18.2%. After optimization, \( H \) was estimated to be 37.2%. Besides the feedback wavelength, the \( H \) of another frequency-conjugate pair (1530 nm and 1590 nm) was measured before and after optimization. During this similar optimization, we regarded \( H \) (frequency-conjugate pairs from 1530 nm and 1590 nm channels) as the feedback and repeated the experiment. Some typical results are shown in Table 1.

There was also a little enhancement of the nearby wavelengths in the optimization, similar to some previous results because of the total signal enhancement [25]. With the improvement of the detection efficiency and algorithms, dense
wavelength division multiplexing was expected in our experimental setup to realize spectral control of SPDC photons with narrower bandwidth. The same experimental setup can also be applied to other linear optics or nonlinear frequency conversion in quantum level.

In conclusion, we put forward a method of manipulating the SPDC process in space and frequency domains theoretically and experimentally. First, the pump phase was modulated to compensate the structure scattering effect of PPLN, which enhanced the SPDC process by 41.9%. Second, a scattering medium was used to simulate the air impurity that SPDC photon pairs propagating in long distance may suffer, and this scattering effect was compensated by 94.6%. Finally, manipulation of the SPDC process with spectral control was realized. This work proved the possibility of manipulating nonlinear signals at quantum level with FBWS and also indicated applications in long-distance QKD, quantum communications, and quantum imaging, especially in complex environments.

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