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Nonlocal dispersion control of a single-photon waveform

So-Young Baek,[*] Osung Kwon, and Yoon-Ho Kim[†]
Department of Physics, Pohang University of Science and Technology (POSTECH), Pohang, 790-784, Korea

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We demonstrate explicitly that a single-photon waveform, conditionally prepared by detecting the trigger photon of the photon pair born in the process of spontaneous parametric down-conversion, becomes broadened and chirped as the result of propagation through a single-mode optical fiber. The pulselike broadening of the single-photon waveform, due to the group velocity dispersion of the optical fiber, is shown to be controllable in a nonlocal way by spectrally filtering the trigger photon.

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Among many nonclassical states in optics that require the quantum theory of radiation to fully understand their properties, the single-photon state most clearly demonstrates the quantized nature of the light field [1]. The single-photon state has been at the heart of many interesting and important principle discussions in quantum physics, such as the complementarity and the nonlocality [2,3], and more recently, it has been recognized as an essential resource for quantum information [4–6]. At present, there exist a number of experimental schemes, based on a variety of diverse physical systems, to realize the single-photon source [7].

Physically, the single-photon state must be associated with a certain spatiotemporal waveform due to the wave nature of the photon. Note that the waveform of the single photon should be understood as the probability distribution for finding a single photon within certain time intervals. Since photonic quantum information processing, such as linear optical quantum computing, can essentially be viewed as quantum interferometry involving multiple single photons [4,5], the shape of the single-photon waveform is an important parameter which is related to the gate fidelity [8,9]. Moreover, the single-photon waveform is often subject to a variety of dispersive media, for example, the beam splitter, the single-mode optical fiber, etc. It is, therefore, of interest to learn how the shape of the single-photon waveform is affected under transmission through the dispersive medium and, importantly, how it can be controlled.

In this paper, we first demonstrate explicitly that a single-photon waveform, conditionally prepared by detecting the trigger photon of the photon pair born in the process of spontaneous parametric down-conversion (SPDC) [10], becomes broadened and chirped as the result of propagation through a dispersive medium: a single-mode optical fiber. It is then demonstrated that the pulselike broadening of the single-photon waveform, due to the group velocity dispersion of the optical fiber, can be controlled nonlocally by spectrally filtering the trigger photon. It is important to note that the nonlocal feature in this experiment is due to the inherent entanglement between the two SPDC photons.

The experimental setup is schematically shown in Fig. 1. A 3-mm-thick type-I BBO crystal was pumped by a 408-nm cw diode laser at 19 mW. A pair of horizontally polarized signal and idler photons, centered at 816 nm, was generated simultaneously and always in pairs by the SPDC process at the BBO crystal. The copropagating signal-idler photon pair was then separated spatially at the 50:50 beam splitter BS. The idler photon, transmitted at the BS, was used as the trigger photon; i.e., upon detection of the idler photon at the trigger detector, the signal photon at the reflected mode of the BS is prepared to be in the single-photon state [11]. The SPDC single-photon source of this type, often called the heralded single-photon state, has long been used for studying quantum properties of the single-photon state [12,13] and, recently, for quantum information applications [14–19]. In this work, we are interested in the waveform of the single photon and how to control it.

The trigger detector consisted of a single-mode fiber coupler and a single photon counting module directly connected to a 2-m-long single-mode fiber. The signal photon was coupled into a long single-mode optical fiber (SMF) with a fiber coupler (FC). IF1 and IF2 are band-pass interference filters. Finally, the single-photon detection events for the signal photon are analyzed with a time correlated single photon counting (TCSPC) electronics, synchronized to the trigger events. Since the histogram recorded at the TCSPC is proportional to the probability distribution of finding a single-photon within a certain time interval (the resolution of TCSPC, PicoHarp 300, is 4 ps per channel), the TCSPC histogram represents the shape of the single-photon waveform in time, provided that the waveform is sufficiently bigger in time than the timing resolution of the electronics.

In classical pulse propagation, the initial spectral bandwidth is one of the important parameters that describe the dispersive pulse spreading. Naturally, we expect that the

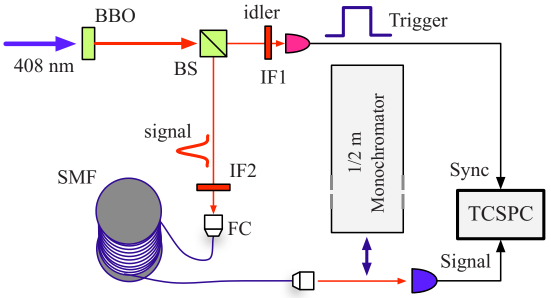

FIG. 1. (Color online) Schematic of the experiment. A TCSPC device analyzes the temporal shape of the single-photon waveform for the signal photon, after it has propagated through SMF.

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[*] simply@postech.ac.kr
[†] yoonho@postech.ac.kr

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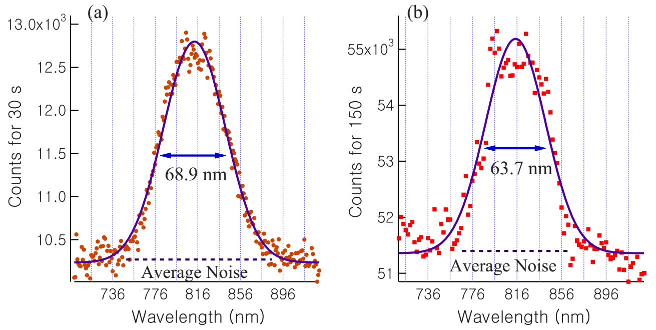

FIG. 2. (Color online) Single-photon spectra measured after (a) 2 m SMF and (b) 1602 m SMF. Solid lines are Gaussian fits to the data.

single-photon waveform spreading will also be critically dependent on the initial bandwidth. To calculate the bandwidth of the photons used in this experiment, it is necessary to start with the biphoton pure state of SPDC

$$|\Psi\rangle = \int d\omega_s d\omega_i S(\omega_s,\omega_i) a_s^\dagger(\omega_s) a_i^\dagger(\omega_i)|0\rangle, \qquad (1)$$

where the subscripts s and i refer to the signal and the idler photons, respectively, and $|S(\omega_s,\omega_i)|^2$ represents the biphoton joint spectrum function that can be calculated from the phase matching condition [20]. Here we have dropped the irrelevant vacuum term. Note that, due to the cw nature of the pump, $\omega_s = \Omega_p/2 + \nu$ and $\omega_i = \Omega_p/2 - \nu$, where Ω_p is the pump frequency and ν is the detuning frequency.

Since the signal and the idler photons in this experiment have the same polarization and copropagating (collinear degenerate type-I SPDC), they have the same initial bandwidth which can be calculated from $|S(\omega_s,\omega_i)|^2$ and is found to be 80 nm at full width at half maximum (FWHM) [20]. In experiment, however, the photons are coupled into SMFs and the spectral bandwidths of the photons may be reduced due to the coupling process as well as SMF propagation.

To have the accurate picture of how much of the spectral bandwidth is actually present, we have measured the spectra of the photons at the output of a 2 m and a 1602 m long (four 400 m long single-mode fiber spools are used) SMFs, see Fig. 1. IF2 is a color filter blocking below 610 nm thus the spectrum of the signal photon is not affected. The measurement was performed using a 1/2 m monochromator (DK 480) with a 1200/mm groove grating blazed at 550 nm. Since the bandwidth is expected to be very broad, we have used rather large entrance and exit slits so that the monochromator resolution was approximately 1.5 nm.

From the data shown in Fig. 2, we conclude that the signal and the idler photons, after they are coupled into and have propagated along the 2 m long SMF, have Gaussian-like spectra with the FWHM bandwidth of 68.9 nm. The temporal width of the conditionally prepared, localized single-photon state for the signal photon at this point can then be estimated by assuming that the waveform is a transform-limited Gaussian with the time-bandwidth product $\Delta t \Delta f = 0.441$ [21]. Under this condition, the single-photon waveform is expected to have the temporal width of 14.2 fs FWHM. We note that this is just a rough estimation and the SPDC heralded single-photon waveform is not in general transform limited [22].

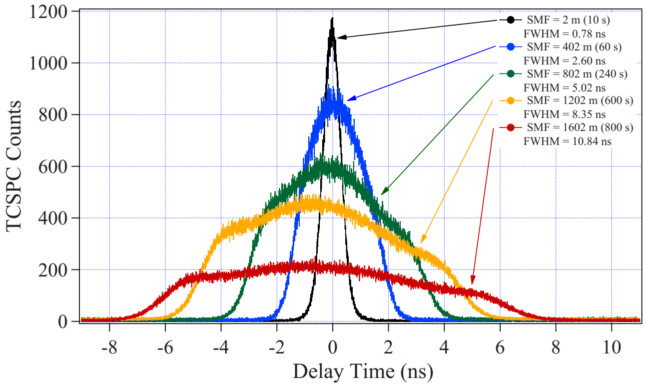

FIG. 3. (Color online) Temporal spreading of the single-photon waveform. IF1 and IF2 are both 80 nm FWHM filters. An offset delay is applied to each of the curve for easy comparison of the waveform spreading.

The TCSPC setup used in this experiment, obviously, cannot measure such a narrow "pulse" as the single-photon detector and other electronic jitter times are orders of magnitude greater than the pulse width to be measured. This is demonstrated in the experimental data for the 2 m SMF shown in Fig. 3. Note that the monochromator is now removed from the setup. Clearly, the FWHM width of 0.78 ns is the result of the timing jitter of the TCSPC electronics and is not an indication of the actual width of the single-photon waveform.

However, when the length of SMF is increased, pulselike spreading of the conditionally prepared localized single-photon can be clearly observed, see Fig. 3. The waveform, initially unrecognizable due to the electronics timing jitter, becomes broadened significantly and is now clearly observable once a SMF spool of 400 m is added [23,24]. And, with more SMF spools added, the single-photon waveform spreading becomes even more pronounced. In this experiment, spectral filters IF1 and IF2 are both 80 nm FWHM band-pass filters centered at 816 nm so that the initial spectra shown in Fig. 2 are unaltered.

Let us now see how the material dispersion affects the single-photon waveform. For this measurement, we have inserted back the previously mentioned monochromator between the 1602 m long SMF and the signal detector, see Fig. 1. IF2 is a color filter blocking below 610 nm and IF1 is a 80 nm FWHM band-pass filter. Since the monochromator functions as a narrowband filter with the effective bandwidth of 1.5 nm FWHM, the TCSPC electronics records the shape of the single-photon waveform that is spectrally filtered with a 1.5 nm band-pass filter. To see how different spectral components are distributed in the broadened single-photon waveform, TCSPC measurements were performed at seven different wavelength settings of the monochromator.

The experimental data are shown in Fig. 4. Figure 4(a) is the temporally broadened single-photon waveform after the 1602 m SMF, taken from Fig. 3. When the monochromator is inserted and the broadened single-photon waveform is spec-

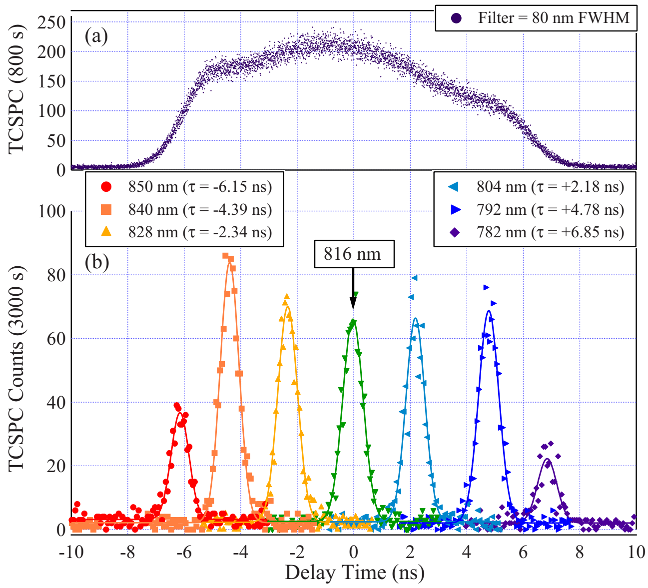

FIG. 4. (Color online) The broadened single-photon waveform after the 1602 m long SMF, (a), is spectrally resolved with a monochromator inserted between the 1602 m SMF and the signal detector, (b).

trally filtered locally with the effective bandwidth of 1.5 nm, see Fig. 4(b), the width of the single-photon waveform decreases significantly so that the average FWHM width is 0.80 ns. In other words, the waveform spreading disappears completely when the single-photon waveform is spectrally filtered locally with the effective bandwidth of 1.5 nm.

In addition, the experimental data shown in Fig. 4(b) demonstrate that the single-photon waveform broadening is due to the group velocity dispersion of the fiber. After the 1602 m long SMF, the redder wavelength components of the single-photon "pulse" exit the fiber earlier (negative τ) than the bluer wavelength components (positive τ) with the degenerate wavelength 816 nm component nearly at the zero delay. The measured delays agree well with the values that are calculated from the group velocities of the photons at the respective wavelengths and the length of the fiber. This means that the broadened single-photon "pulse" is severely chirped, just as a classical ultrafast pulse propagating through a dispersive medium. Since the single-photon waveform behaves just like a classical ultrafast pulse, it should be possible to compress the chirped single-photon "pulse" using common dispersion management techniques based on a prism pair, a grating pair, chirp mirrors, etc.

The spreading of the single-photon waveform observed in Fig. 3, therefore, can be understood by considering the material dispersion, the initial bandwidth, and the initial pulse width, just as in the case of ultrafast pulse propagation through a dispersive medium. The width of the broadened (chirped) single-photon waveform can be estimated using the initial FWHM bandwidth $\Delta\lambda$ (in nm) and the dispersion coefficient D_λ [in ps/(km-nm)] of the medium, where $D_\lambda = -(d^2n/d\lambda_0^2)\lambda_0/c$ with λ_0 and c are the central wavelength and the speed of light in vacuum, respectively, and n is the wavelength dependent refractive index of the medium which in this case is fused silica. The FWHM temporal pulse width $\Delta\tau$ (in ps) of the single-photon waveform, after it has propagated through a dispersive medium of length z (in m) is then given as [25]

$$\Delta\tau = z\Delta\lambda|D_\lambda|. \tag{2}$$

Using the above formula, it is found that the initial single-photon waveform of 68.9 nm bandwidth will spread to a new waveform of 2.73 ns FWHM and of 10.9 ns FWHM after propagating through a 402 and 1602 m single-mode optical fibers, respectively. The data shown in Fig. 3 are in good agreement with this prediction. Therefore, albeit the initial temporal width of the single-photon waveform cannot be measured directly in experiment, we can quantitatively estimate, with good accuracy, the final pulse width of the single-photon waveform using Eq. (2).

We now discuss how the dispersive spreading of the single-photon waveform can be controlled nonlocally, i.e., without directly manipulating the signal photon. First, note that the signal-idler photon pair of SPDC is initially born in the entangled state shown in Eq. (1). The quantum state of the idler trigger photon, therefore, is found to be in a mixed state of the form

$$\rho_i = \int d\omega_i F_i(\omega_i) a_i^\dagger(\omega_i)|0\rangle\langle 0|a_i(\omega_i), \tag{3}$$

where $F_i(\omega_i)$ is the transmission function of the spectral filter IF1 in Fig. 1, $\omega_s = \Omega_p/2 + \nu$, and $\omega_i = \Omega_p/2 - \nu$.

Upon detection of the idler trigger photon, the signal photon takes the form of a localized single-photon state whose quantum state is described as

$$\rho_s = \mathrm{Tr}_i[|\Psi\rangle\langle\Psi|\rho_i], \tag{4}$$

where $|\Psi\rangle$ is the biphoton state of SPDC in Eq. (1). Although ρ_s is a mixed state in general, the heralded single-photon source of this type has been shown to exhibit Hong-Ou-Mandel–type quantum interference, which makes it a useful tool in photonic quantum information research [17]. Note that, recently, it has been shown theoretically that it is possible to generate a pure single-photon state by spectrally engineering the SPDC two-photon state [18,22].

It is clear from Eq. (4) that the single-photon waveform for the signal photon should have the spectral bandwidth equal to

$$|S(\omega_s,\omega_i)|^2 F_i(\omega_i). \tag{5}$$

Since $F_i(\omega_i)$ is just the filter function, the broadest bandwidth that the signal photon can have, hence the shortest initial single-photon pulse width, is determined by the joint spectrum function $|S(\omega_s,\omega_i)|^2$ due to the phase matching condition of the SPDC process. The above relation then provides us the opportunity for nonlocally controlling the spectral bandwidth of the signal photon, hence nonlocally controlling the temporal dispersion of the single-photon waveform, by properly choosing the filter transmission function $F_i(\omega_i)$ for the idler photon which is used as the trigger [26].

To demonstrate the nonlocal dispersion control of the single-photon waveform, the same experimental setup shown in Fig. 1 is used but IF1 is now a spectral filter with a 10 nm

FWHM centered a 816 nm. IF2 is the same 80 nm FWHM spectral filter which does not affect the signal photon bandwidth in any direct way. In this case, according to Eq. (5), the use of narrowband spectral filter IF1 for the trigger photon effectively and nonlocally reduces the bandwidth of the conditionally prepared single-photon state for the signal photon. The reduced-bandwidth signal photon will then have a wider single-photon waveform (or pulse width) and the waveform will spread lesser compared to the case of a narrower single-photon waveform, when propagating through the same dispersive medium.

The experimental results are shown in Fig. 5. The data clearly demonstrate that the waveform spreading for the signal photon is reduced significantly, compared with the case of Fig. 3, in a nonlocal way by spectrally filtering the trigger photon.

In summary, we have observed pulselike spreading of a single-photon waveform, conditionally prepared by detecting the idler trigger photon of the SPDC photon pair, when propagated through a dispersive medium: a single-mode optical fiber. We have demonstrated that the broadening of the single-photon waveform is due to the group velocity dispersion (the broadened waveform is chirped) and that it can be controlled nonlocally by spectrally filtering the idler trigger photon. Since the SPDC single-photon source has strong potential applications in quantum information experiments [8,9,11,14–18], the observed effect is of importance in linear optical quantum computing and quantum cryptography where fiber-optic transmission of a single-photon is often necessary.

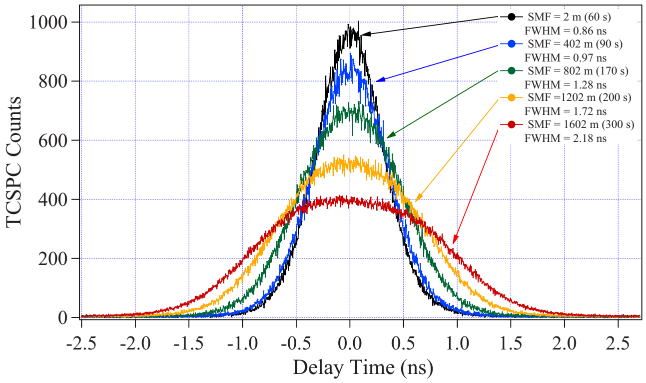

FIG. 5. (Color online) Demonstration of nonlocal dispersion control of a localized single-photon. The trigger photon is now filtered with a 10 nm bandwidth filter IF1. IF2 remains at 80 nm. The effect of group velocity dispersion has almost disappeared when compared with Fig. 3.

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