Nonlocal Dispersion Cancellation using Entangled Photons

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Classically, a pair of optical pulses traveling through two dispersive media will become broadened and, as a result, the degree of coincidence between the optical pulses will be reduced. Surprisingly, for a pair of entangled photons, nonlocal dispersion cancellation in which the dispersion experienced by one photon cancels the dispersion experienced by the other photon is possible. In this paper, we report the first experimental demonstration of nonlocal dispersion cancellation using entangled photons. The degree of two-photon coincidence is shown to increase beyond the limit attainable without entanglement. Our results have important applications in fiber-based quantum communication and quantum metrology.

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Consider a ultrafast optical pulse propagating through a dispersive media. Due to the group velocity dispersion, the wave packet of the pulse will get broadened. When two such pulses, initially coincident in time, travel through two different dispersive media, each pulse will experience dispersion independently of the other. The dispersive broadening of the two wave packets will then reduce degree of temporal coincidence.

When a pair of entangled photons is considered instead of two classical ultrafast pulses, a surprising result can occur: the dispersion experienced by one photon cancels the dispersion experienced by the other photon is possible. This phenomenon is known as nonlocal dispersion cancellation [1]. Consider a pair of entangled photons, nonlocal dispersion cancellation in which the dispersion experienced by one photon cancels the dispersion experienced by the other photon is possible. In this paper, we report the first experimental demonstration of nonlocal dispersion cancellation using entangled photons.

Let us first briefly discuss the theory behind nonlocal dispersion cancellation [1, 4]. Consider a pair of spontaneous parametric down-conversion (SPDC) photons generated at a BBO crystal pumped by a monochromatic pump, see Fig. 1. The quantum state of the photon pair,

$$|\psi\rangle = \int d\omega_1 d\omega_2 S(\omega_1, \omega_2) a^\dagger(\omega_1) a^\dagger(\omega_2)|0\rangle,$$  \hspace{1cm} (1)

is an entangled state since the two-photon joint spectral amplitude $S$ is non-factorizable, i.e., $S(\omega_1, \omega_2) \neq S(\omega_1)|\psi\rangle$}

FIG. 1: Each photon of the entangled photon pair is subject to different dispersion $\beta_1$ and $\beta_2$. The coincidence circuit measures $G^{(2)}(t_1 - t_2)$.

$$S(\omega_1)S(\omega_2),$$

due to the monochromatic nature of the pump [12, 13]. The joint detection probability of the two photons $D_1$ and $D_2$ is proportional to the Glauber second-order correlation function

$$G^{(2)}(t_1, t_2) = |\langle 0|E_2^{(+)}(t_2)E_1^{(+)}(t_1)|\psi\rangle|^2, \hspace{1cm} (2)$$

where $E_i^{(+)}(t_i) = \int d\omega a(\omega) e^{i(\nu_k z_i - \omega t_i)}$, the positive frequency part of the electric field operator at detector $D_i$, and $E_2^{(+)}$ is defined similarly. Since each photon has spectral distribution centered at certain central frequency, $\Omega_1$ and $\Omega_2$, and assuming that the photons propagate through dispersive media of length $z_1$ and $z_2$ as shown in Fig. 1, the wave number of the photon can then be expressed as $k_i(\Omega_i \pm \nu) = k_i(\Omega_i) \pm \alpha_i \nu + \beta_i \nu^2$ ($i = 1, 2$). Here $\nu$ is the detuning frequency from the central frequency, and $\alpha$ and $\beta$ are the first-order and the second-order dispersion which are responsible for the wave packet delay and the wave packet broadening, respectively.

For a monochromatic pump, the quantum state in eq. (1) can be re-written as $|\psi\rangle = \int d\nu S(\nu) a^\dagger(\Omega_1 + \nu) a^\dagger(\Omega_2 - \nu)|0\rangle$, with $S(\nu) = \text{sinc}(\nu DL/2)$ for nondegenerate type-I SPDC. Here, $L$ and $D \equiv 1/\nu_2 - 1/\nu_1$ are the BBO crystal thickness and the inverse group velocity difference between the photon pair in the BBO crystal,
where \( \bar{\tau} \) been looking for: a positive dispersion

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ginally shown in Fig. 2. We first describe the entangled
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Finally, the joint spectral amplitude as a Gaussian function is given as [14]

\[
G^{(2)}(t_1 - t_2) \approx C e^{(t_1-t_2-\bar{\tau})^2/2\sigma^2},
\]

where \( \bar{\tau} = \alpha_2z_2 - \alpha_1z_1 \) and \( \sigma^2 = \gamma D^2L^2 + (\beta_1z_1 + \beta_2z_2)^2/\gamma D^2L^2 \) are the overall time delay between the signal and the idler photons and the width of \( G^{(2)} \) function after propagating through the dispersion media, respectively. Note that \( C = \pi/\sqrt{\gamma^2D^4L^4 + (\beta_1z_1 + \beta_2z_2)^2} \) is an unimportant proportionality factor.

Finally, the full width at half maximum value of the temporal width of \( G^{(2)} \) function is given as [14]

\[
\Delta t \approx 2\sqrt{2\ln 2/\gamma D^2L^2(\beta_1z_1 + \beta_2z_2)}. 
\]

The above equation shows precisely the effect we have been looking for: a positive dispersion \( \beta_1 \) experienced by photon 1 can be cancelled by a negative dispersion \( \beta_2 \) experienced by photon 2. Such nonlocal dispersion cancellation effect is shown to occur only if photon 1 and photon 2 are in a specific entangled state [4].

The experimental setup to implement the nonlocal dispersion cancellation effect discussed above is schematically shown in Fig. 2. We first describe the entangled photon generation part of the experimental setup which is not shown in the figure. A 3 mm thick type-I \( \beta \)-barium borate (BBO) crystal is pumped by a cw diode pump laser operating at 408.2 nm, generating a pair of collinear frequency-nondegnerate entangled photons centered at 896 nm and 750 nm via the SPDC process. Type-I collinear phase matching ensures that both the signal and idler photons of SPDC have very broad spectra centered at 896 nm (over 28 nm at FWHM) and 750 nm (over 20 nm at FWHM), respectively. Both photons are, however, strongly quantum correlated in wavelength: if the signal photon is found to have the wavelength \( \lambda_1 \), then its conjugate idler photon will be found to have the wavelength \( \lambda_2 = \lambda_p\lambda_1/\lambda_p - \lambda_2 \), where \( \lambda_p = 408.2 \) nm. To efficiently couple these photons into single-mode optical fibers, the pump laser was focused with a \( f = 300 \) mm lens and the SPDC photons were coupled into single-mode optical fibers using \( \times 10 \) objective lenses located at 600 mm from the crystal. The co-propagating photons were then separated spatially by using a beam splitter and two interference filters with 100 nm FWHM bandwidth, each centered at 896 nm and 750 nm.

The 896 nm centered signal photon (\( \lambda_1 \) in Fig. 2) is then coupled into a 1.6 km long single-mode optical fiber which introduces positive dispersion \( \beta_1 \) to the photon. As we shall show later, the effect of a positive dispersion material to the entangled photon is to broaden the biphoton wave packet [5, 15, 16].

To demonstrate the nonlocal dispersion cancellation effect, it is necessary to introduce negative dispersion to the idler photon (\( \lambda_2 \) in Fig. 2). Among many potential methods for introducing negative dispersion [17, 18], methods based on a grating pair or a prism pair are often used in ultrafast optics [19, 20]. In our experiment, we have used the grating pair method to introduce negative dispersion to the idler photon [21].

The idler photon is first coupled into a 2 m long single-mode fiber and the fiber polarization controller (FPC) is used to set the polarization to maximize the diffraction efficiency. The grating pair \( G_1 \) and \( G_2 \) and a plane mirror is used to setup the negative dispersion device shown in Fig. 2 [22]. The distance between the two gratings is set at 10 cm and the deviation angle at 750 nm is 8°. Since the grating \( G_2 \) is not big enough to cover the full bandwidth, the grating pair system slightly reduces the spectral bandwidth of the idler photon. After experiencing negative dispersion, the idler photon is coupled into a different 2 m long single-mode fiber for collimation and is sent through a 1/2 m monochromator (CVI DK480) which functions as a tunable narrowband filter. The monochromator M is used to spectrally-resolve the entangled biphoton wave packet [12, 16].

Finally, the entangled biphoton wave packet is mea-
We first observed the entangled photon wave packet when the signal photon was passed through a 1.6 km single-mode optical fiber which introduces the positive dispersion $\beta_1$. The total length of the idler photon’s passage through the single-mode optical fiber is 4 m. Since we hope to observe the full TCSPC histogram which represents the dispersion broadened entangled photon wave packet, the monochromator M was not used for this measurement. The experimental data are shown in Fig. 3(a). The measured TCSPC histogram has the FWHM width of 3.861 ns which is significantly bigger than the timing resolution of the measurement system and is due to the dispersive broadening of the entangled photon wave packet.

To experimentally demonstrate the nonlocal dispersion cancellation effect, it is necessary to introduce negative dispersion $\beta_2$ to the idler photon so that the positive dispersion $\beta_1$ experienced by the signal photon is cancelled by the negative dispersion $\beta_2$ experienced by the idler photon [1, 4]. The experiment was performed by directing the idler photon through the grating pair system for negative dispersion, while the signal photon’s passage through the 1.6 km single-mode fiber was not changed. As before, the monochromator M was not used for this measurement as we aim to observe the full TCSPC histogram.

The experimental data for this measurement are shown in Fig. 3(b). While the data clearly demonstrate reduced FWHM (2.436 ns) of the TCSPC histogram when compared to Fig. 3(a), Fig. 3 itself is quite insufficient for a conclusive demonstration of the nonlocal dispersion effect. It is because the grating pair system slightly reduces the spectral bandwidth of the idler photon and the reduced FWHM shown in Fig. 3(b) could be solely due to the bandwidth reduction.

It is thus critically important to attribute how much of the wave packet reduction observed in Fig. 3 has actually come from the nonlocal dispersion cancellation effect, if any. This critical measurement was accomplished by spectrally resolving the two entangled photon wave packets in Fig. 3 by introducing the monochromator M in the path of the idler photon [15, 16]. The monochromator was set to have roughly 1.2 nm of passband and it functions as a wavelength-variable bandpass filter. The TCSPC histograms measured for several values of the wavelength setting of the monochromator correspond to spectrally resolved components of the entangled photon wave packets shown in Fig. 3.

Observation of nonlocal dispersion cancellation then requires comparing the temporal spacing between the spectrally resolved components of the entangled photon wave packets. If the temporal spacing between the spectrally resolved components are reduced by the introduction of the grating pair, it conclusively confirm the nonlocal dispersion cancellation effect in Ref. [1, 4]. On the other hand, if the temporal separation remains the same while some of the components showing reduced amplitudes, it would mean that the overall wave packet reduction is actually due to the bandwidth filtering.

The experimental data are shown in Fig. 4. In Fig. 4(a), the entangled photon wave packet with positive dispersion $\beta_1$ introduced in the path of the signal photon is spectrally resolved. In Fig. 4(b), we show the spectrally resolved entangled photon wave packet when both $\beta_1$ and $\beta_2$ are introduced. Comparing Fig. 4(a) and Fig. 4(b), we observe that the temporal spacings between the spectrally resolved components are reduced when the idler photon is subject to negative dispersion $\beta_2$. This is a clear and conclusive signature of the nonlocal dispersion cancellation effect. It is also interesting to observe that certain spectral components (most notably, 740 nm and 760 nm) are strongly attenuated, causing reduction of the entangled photon wave packet.

The above observations allow us to conclude that the reduced entangled photon wave packet in Fig. 3(b) is due to both the nonlocal dispersion cancellation effect and the bandwidth reduction by the grating pair system. The experimental data in Fig. 4 show that the reduction of the temporal spacing between 740 nm and 760 nm is 478 ps. To see what the theoretically expected value is, we need to make use of eq. (3). The introduction of $\beta_2$...
reduces the width of $G^{(2)}$ function by
\[ \Delta t_{\text{NDC}} \approx 2 \sqrt{\frac{2 \ln 2}{\gamma D^2 L^2}} \beta_1 \beta_2. \]

In our experiment, $DL = 88.9$ fs and $\beta_1 \beta_2$ for the grating pair system is given as $22,421 (1992)$.\[2\]

The theoretically calculated value of the reduction of the biphoton wave packet, therefore, is approximately 496 ps. Considering the measurement errors for evaluating $\beta_2 \beta_2$, our experimental observation agrees very well with the theoretical prediction.

We therefore estimate that, out of 1.425 ns reduction of the wave packet shown in Fig. 3, roughly 478 ps comes from the nonlocal dispersion cancellation effect and the rest comes from the bandwidth filtering at the grating pair. To improve the nonlocal dispersion cancellation effect, it is necessary to eliminate the bandwidth reduction effect of the grating pair system and it can be done by replacing the grating $G_2$ with a larger one. We expect that the nonlocal dispersion cancellation effect reported here could play an important role in entangled photon quantum metrology $[23]$.\[3\]

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[8] Nonlocal dispersion cancellation demonstrated here is a completely different physical effect from the dispersion insensitivity observed in Hong-Ou-Mandel interference $[10]$. Hong-Ou-Mandel interference is a first order correlation effect, $G^{(1)}(t)$, which is related only to the power spectrum of the biphoton field, just as classical Michelson interference $[11]$. Thus, a dispersion element placed precisely in the path of one photon before the photon pair is brought together at a beamsplitter does not affect the Hong-Ou-Mandel dip. On the other hand, nonlocal dispersion cancellation reported here is a genuine second order correlation effect, $G^{(2)}(t_1-t_2)$, in which the dispersion experienced by one photon is actually cancelled by the dispersion experienced by its entangled pair photon.
[14] We have assumed $\gamma^2 D^4 L^4 < (\beta_1 \beta_2)^2$. This condition holds in general as the crystal parameter $DL$ is much smaller than the external parameters $\beta_1 \beta_2$.
[21] In experiment, it is necessary to introduce negative dispersion bigger than the timing resolution of the TCSPC system which is on the order of several ps. The prism pair normally can offer negative dispersion on the order of several tens of femtoseconds only.
[22] The grating $G_1$ and $G_2$ are Spectrogon 715.701.990 and
715.701.350, respectively. The grating specifications can be found at [http://www.spectrogon.com/gratpulse.html](http://www.spectrogon.com/gratpulse.html).