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High-visibility nonclassical interference between intrinsically pure heralded single photons and photons from a weak coherent field

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We present an experiment of nonclassical interference between an intrinsically pure heralded single-photon state and a weak coherent state. Our experiment demonstrates that, without the use of bandpass filters, spectrally pure single photons can have high-visibility ($89.4 \pm 0.5\%$) interference with photons from a weak coherent field. Our scheme lays the groundwork for future experiments requiring quantum interference between photons in nonclassical states and those in coherent states.

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Nonclassical interference between independent photons (NIBIP) plays a very important role in quantum information processing. One kind of such NIBIP is the interference between photons from different spontaneous parametric down-conversion (SPDC) sources, which is vital to the preparation of the multiphoton entangled state [1] needed for implementing quantum networks [2] and quantum computing algorithms [3]. Another kind of NIBIP is the interference between single photons from SPDC and weak coherent, i.e., local oscillator (LO), photons from the laser source. This kind of interference is fundamental for homodyne detection [4], and is also the key to quantum-optical catalysis [5] and quantum circuits [6,7].

The first experiment of nonclassical interference between heralded single photons from SPDC and LO sources was carried out by Rarity *et al.* in 1997 [8,9]. Since LO photons have no phase correlation with SPDC photons, i.e., signal and idler photons, the sources in the experiment can be thought of as independent sources. However, in general, the signal and idler photons generated from SPDC have correlated frequencies, and thus the heralded single photons based on SPDC are not pure in terms of their spectrotemporal modes. This lack of purity inevitably degrades the indistinguishability between the signal (or idler) and LO photons, resulting in low-visibility interference. Traditionally, bandpass filters were employed to improve the indistinguishability and interference visibility. Spectral filtering is one way to improve the indistinguishability between the signal and LO photons, but this method has the drawback of severely decreasing the count rate. Recent advances in the preparation of a pure single-photon source help solve this problem. When a phase-matching condition is carefully engineered, a pure heralded single-photon state can be generated in SPDC crystals [10–13] and photonic crystal fibers [14–17].

By using SPDC with the group-velocity matching condition in a potassium-dihydrogen-phosphate (KDP) crystal [12], we prepared an intrinsically pure heralded single-photon state, which interfered with a weak coherent state in a three-photon Hong-Ou-Mandel (HOM) interference [18] without spectral filtering. Our experiment demonstrates that spectrally pure heralded single photons can have high-visibility interference with photons from a weak coherent field without any spectral filtering.

The two-photon component of the final state of SPDC can be expressed as

$$|\psi_{si}\rangle = \int_0^\infty \int_0^\infty d\omega_s d\omega_i\, f(\omega_s,\omega_i)\hat{a}_s^\dagger(\omega_s)\hat{a}_i^\dagger(\omega_i)|0\rangle, \quad (1)$$

where $f(\omega_s,\omega_i) = \phi(\omega_s,\omega_i)\alpha(\omega_s+\omega_i)$ is the joint spectral distribution function [19], $\phi(\omega_s,\omega_i)$ and $\alpha(\omega_s+\omega_i)$ are the phase-matching function and the pump-envelope function, and the subscripts s and i denote signal and idler photons, respectively. By carefully choosing the phase-matching condition, as described below, the joint spectral distribution function of the signal and idler photons can attain a factorable state [11], which satisfies

$$f(\omega_s,\omega_i) = g_s(\omega_s)g_i(\omega_i). \quad (2)$$

The purity of the signal is defined as $\gamma \equiv \mathrm{Tr}(\hat{\rho}_s^2)$, where $\hat{\rho}_s = \mathrm{Tr}_i(|\psi_{si}\rangle\langle\psi_{si}|)$ is the reduced density operator of the signal. This purity is determined by the factorability of the joint spectral distribution $f(\omega_s,\omega_i)$ [12] and can be calculated numerically, using Schmidt decomposition [10], as the inverse of the Schmidt number [13]. In the case of the KDP crystal, the group velocity (GV) of the 415-nm pump [extraordinary ray (e ray)] equals the GV of the 830-nm signal [ordinary ray (o ray)], and is far from the GV of the 830-nm idler (e ray). Under this condition, the signal and idler are in a factorable state [11]. Figures 1(a)–1(c) present the theoretical calculation of the (a) pump-envelope function $|\alpha(\omega_s+\omega_i)|^2$, (b) phase-matching function $|\phi(\omega_s,\omega_i)|^2$, and (c) joint spectral distribution $|f(\omega_s,\omega_i)|^2$, respectively, when a pump beam [415 nm, full width at half maximum (FWHM) = 2.3 nm] is focused on a 15-mm-long KDP crystal. It is obvious that Fig. 1(a) is frequency entangled; however, Fig. 1(b) is sharp and functions as a δ function. As a result, the product of Figs. 1(a) and 1(b) is factorable, as shown in Fig. 1(c). Figure 1(d) is the experimentally measured joint spectral distribution, and will be explained in detail later.

Next we considered the interference between the signal and LO photons, with the idler as the heralder, as shown in Fig. 2. If both the signal and LO were single photons that

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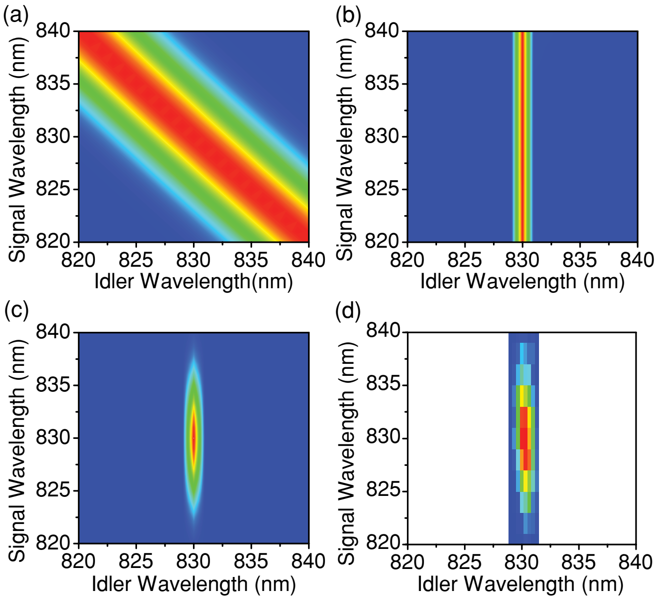

FIG. 1. (Color online) Density plots of the (a) pump-envelope function, (b) phase-matching function, (c) calculated joint spectral distribution function, and (d) experimentally observed joint spectral distribution of the SPDC that we employed.

were indistinguishable from each other, we might expect a normal HOM interference [18]. However, in our case, the signal could be treated as a single photon when heralded by the sister idler photon. Thus, a three-fold coincidence is necessary to ensure that a single signal photon interferes with an LO photon. In addition, the mean photon number in an LO pulse should be low enough so that the probability of finding more than two LO photons is negligible. Another essential factor in this experiment is the indistinguishability between the signal and LO photons. Both the identity in spectrotemporal profiles and their purity, as described above, are essential to ensure indistinguishability [20,21].

Assuming that the spectrotemporal modes of both the signal and LO are pure, the threefold coincidence count between the signal, idler, and LO as a function of the delay τ between the signal and LO can be expressed as [22,23]

$$P(\tau) = \frac{1}{2} - \frac{\sigma_s \sigma_L}{\sigma_s^2 + \sigma_L^2} \exp\left[-\frac{\sigma_s^2\sigma_L^2\tau^2 + 4\delta^2}{2(\sigma_s^2+\sigma_L^2)}\right], \quad (3)$$

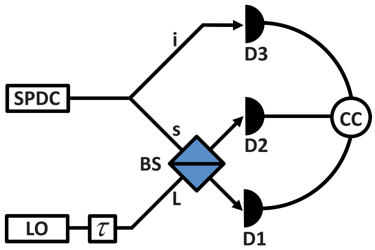

FIG. 2. (Color online) Schematic model of the experiment. The LO photon (L), after a delay τ, interfered with the signal (s) at the beam splitter (BS) with the idler (i) as a heralder. These photons were detected by three detectors and recorded by a threefold coincidence counter (CC).

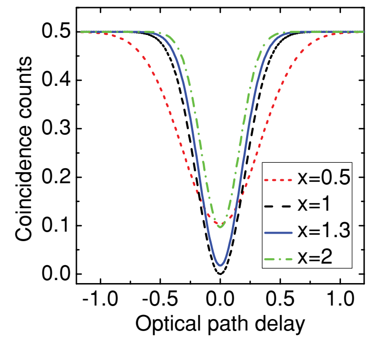

FIG. 3. (Color online) Theoretical calculation of HOM interference between pure signal and LO photons with identical central wavelengths ($\delta = 0$) and different bandwidth ratios ($x = \sigma_s/\sigma_L$). For $x = 1$, we obtain $V = 1$. When $x = 1.3$, 2, and 0.5, $V = 0.96$, 0.81, and 0.79, respectively.

where σ_s and σ_L are the bandwidths of Gaussian spectra for the signal and LO, respectively, and δ is the central frequency difference between the signal and LO. When $\delta = 0$, the interference visibility V is written as

$$V \equiv \frac{P(\infty) - P(0)}{P(\infty)} = \frac{2x}{1+x^2} = \operatorname{sech}\xi, \quad (4)$$

where $x = \sigma_s/\sigma_L$ and $\xi = \ln(x)$. Perfect interference, or $V = 1$, is obtained when $\delta = 0$ and $x = 1$. Figure 3 shows the calculated HOM interference pattern $P(\tau)$ for $\delta = 0$ and some different values of x. We note that V is still as large as 0.96 when $x = 1.3$, indicating that a small difference between the bandwidths of the LO and signal photons does not have a large influence on the interference visibility.

The experimental setup is displayed in Fig. 4. Femtosecond pulses (temporal duration ~150 fs, center wavelength = 830 nm, FWHM 7.1 nm) from the mode-locked titanium:sapphire laser (Coherent, Mira900) were frequency doubled by an 0.8-mm-thick lithium triborate (LBO) crystal and were used as the pump source for the SPDC. Pump pulses with power of 60 mW passed through a 15-mm-long KDP crystal, which was cut for type-II (eoe) degenerate phase matching at 830 nm ($\theta = 67.8°$). The down-converted photons, i.e., the signal (o ray, FWHM = 9.3 nm) and idler (e ray, FWHM = 1.9 nm) were separated by a polarizing beam splitter. Then, idler photons were coupled into a single-mode fiber, and signal photons were coupled into a 50:50 single-mode fiber beam

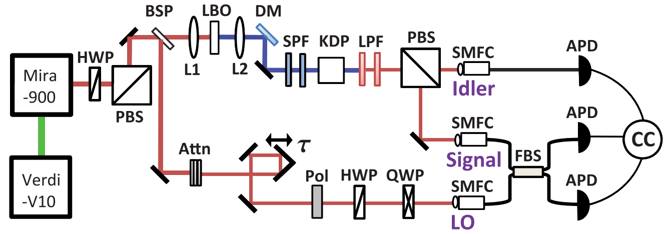

FIG. 4. (Color online) The experiment setup. CC (coincidence counter), APD (avalanche photodiodes), FBS (fiber beam splitter), SMFC (single-mode fiber coupler), PBS (polarizing beam splitter), QWP (quarter-wave plate), HWP (half-wave plate), Pol (polarizer), Attn (attenuator), BSP (beam sampler), DM (dichroic mirror), SPF (short-wave pass filter), and LPF (long-wave pass filter).

splitter (FBS) (Thorlabs, FC830-50B-FC). Fundamental laser pulses that were reflected from a beam sampler and highly attenuated by neutral density filters were used as LO photons. The polarization of the LO was adjusted by a polarizer, a half-wave plate, and a quarter-wave plate so that we could obtain the highest possible interference visibility between the signal and LO. Finally, all of the collected photons were sent to three silicon avalanche photodiode (APD) detectors (PerkinElmer, SPCM-AQRH14) connected to a three-fold coincidence counter.

To check the factorability and purity of the prepared SPDC photon pairs, we measured the joint spectral distribution by putting a pair of monochromators on the signal and idler arms. The coincidence counts between signal and idler were recorded while scanning the wavelengths of the two monochromators. The measured joint spectral distribution is shown in Fig. 1(d). The Schmidt number [10,12] calculated from Fig. 1(d) was 1.03, corresponding to a purity of 0.97, which ensures the high purity of the state we prepared.

Figure 5(a) shows the result of the threefold coincidence-count rate as a function of the optical path delay τ. The observed single-count rates of the idler, signal, and LO were 9, 9, and 600 kHz, respectively. In this case, the average photon number per LO pulse was less than 0.02. The twofold coincidence-count rate between the signal and idler was 1.2 kHz, while the threefold coincidence-count rate between the signal, idler, and LO was 4.8 Hz. The threefold counting rate exhibited a steep HOM dip around $\tau = 0$, as predicted in Fig. 3. The maximum visibility observed was $89.4 \pm 0.5\%$, with a FWHM of 50.1 μm. In contrast, as shown in Fig. 5(b), the visibility of a twofold coincidence count between the signal and LO was only $29.5 \pm 0.3\%$. In this measurement, the corresponding single count of both the signal and LO was 12 kHz.

With the idler as a heralder, the interference between the signal and weak LO can be viewed as an interference between two single-photon states, which can achieve 100% visibility in the ideal case. On the contrary, without the heralding by the idler, the twofold interference is only a classical interference between a thermal signal state and a weak coherent LO state, and the upper limit of the visibility for the general classical two-photon interference is only 50% [24]. This is the reason for the much higher visibility in Fig. 5(a) than in Fig. 5(b).

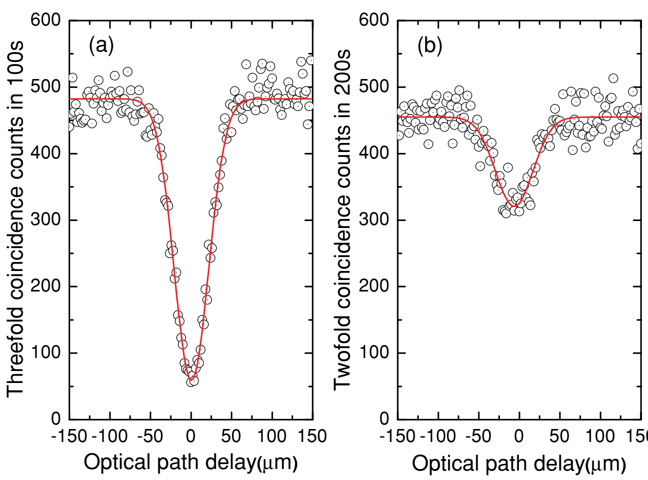

FIG. 5. (Color online) Observed HOM interference. (a) Threefold coincidence counts between the LO and heralded signal, with the idler as the heralder. (b) Twofold coincidence counts between the LO and signal, without the heralder. No background signals were subtracted in either (a) or (b). The solid curves represent Gaussian fits to the data points.

In the experiment, the FWHM of the signal and LO spectra were 9.3 nm and 7.1 nm, respectively. According to Eq. (3), the FWHM of the threefold HOM dip was expected to be 44.5 μm, which is in reasonable agreement with the experimental value of 50.1 μm. The slightly longer value in the experiment might originate from stretched UV pump duration caused by group velocity dispersion (GVD) in the second-harmonic-generation (SHG) crystal. We also expect, using Eq. (4) and the measured FWHMs, that $V = 96.5\%$. The measured visibility $89.4 \pm 0.5\%$ was slightly smaller than the theoretically expected value. The result may derive from the GVD effect in the SHG crystal [8], and the background accidental counts. Nevertheless, in comparison with the first experiment of nonclassical interference from independent sources [8], which employed a 3-nm bandpass filter and achieved a visibility of $62.8 \pm 1.2\%$ in threefold and $4.6 \pm 0.2\%$ in twofold HOM interferences, we achieved significant improvement not only in the visibility but also in the efficiency, using the spectrally pure single-photon source.

Mosley *et al.* [12,13] demonstrated that pure heralded single photons can be generated through group-velocity-matched SPDC, without spectral filtering. In their experiment, two independent KDP crystals were pumped to produce two identical pairs of photons. The observed interference visibilities were $94.4 \pm 1.6\%$ between idlers and $89.9 \pm 3.0\%$ between signals. It should be emphasized that our scheme was different from their experiment. Both interfering photons in Refs. [12] and [13] were in heralded single-photon states, while in our approach, one source was in a heralded single-photon state, and the other was in a weak coherent state. Our experiment manifested that spectrally pure single-photon states can exhibit high-visibility nonclassical interference, even with classical, weak coherent states.

Many subareas of quantum information processing [3,6,7,25–31] require nonclassical interference of photons from independent sources. Traditionally in these experiments, spectral filtering has been utilized to improve visibility at the expense of decreasing event efficiency. When the system expands to utilize more photons, this may become a severe problem. With the scheme proposed in this Rapid Communication, we can improve the visibility without such expense so that the system has a better expandability.

Another application of our approach is homodyne-based quantum metrology and quantum information protocols. Homodyne detection is a widely used technique in quantum optics, in which a quantum signal mixes with a strong LO on a beam splitter. Conventionally, the LO and signal are filtered by narrow bandpass filters to match the modes and improve their indistinguishability [4]. The use of bandpass filters, of course, decreases the event efficiency, increasing the duration of the acquisition process. To date, preparing the signal in a pure spectrotemporal mode, and at the same time matching the modes of the LO and signal, is still a challenging task [4]. The high-visibility interference between the signal and LO in our experiment provides a good solution to the mode-matching problem in homodyne detection. In addition, the recent proposal on the preparation of high-photon-number NOON states by mixing SPDC photons with coherent photons [32] also highlights the need for a pure SPDC source for spectrotemporal mode matching.

In conclusion, we have experimentally demonstrated high-visibility nonclassical interference between a spectrally pure heralded single-photon state and a weak coherent LO state. The observed threefold HOM interference exhibited a visibility of $89.4 \pm 0.5\%$, which is superior to previous results, without any spectral filtering. Our scheme has promising applications in quantum metrology and quantum information experiments requiring indistinguishability and quantum interference between photons in nonclassical states and those in coherent states.

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