Quantum interference between heralded single photon state and coherent state*

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Balanced homodyne detection has been introduced as a reliable technique of reconstructing the quantum state of a single photon Fock state, which is based on coupling the single photon state and a strong coherent local oscillator in a beam splitter and detecting the field quadrature at the output ports separately. The main challenge associated with a tomographic characterization of the single photon state is mode matching between the single photon state and the local oscillator. Utilizing the heralded single photon generated by the spontaneous parametric process, the multi-mode theoretical model of quantum interference between the single photon state and the coherent state in the fiber beam splitter is established. Moreover, the analytical expressions of the temporal-mode matching coefficient and interference visibility and relationship between the two parameters are shown. In the experimental scheme, the interference visibility under various temporal-mode matching coefficients is demonstrated, which is almost accordant with the theoretical value. Our work explores the principle of temporal-mode matching between the single photon state and the coherent photon state, originated from a local oscillator, and could provide guidance for designing the high-performance balanced homodyne detection system.

Keywords: heralded single photon state, coherent state, quantum interference, balanced homodyne detection

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1. Introduction

With the present development of quantum information technologies, including quantum crytography,[1–3] quantum computation,[4] and quantum teleportation,[5] a single photon source[6] has attracted much interest in recent years. Many different implementations have been investigated for single photon production, for example, a spontaneous parametric process, single molecule or atom excitation, quantum dots, as well as color centers in diamond.[7] The spontaneous parametric process has been extremely useful for generating heralded single photon, in which detecting one of the new-born twin photons heralds the presence of the other twin photons.[8,9]

Quantum state construction of single photon and measurement of its Wigner functions have become a focus in quantum optics.[10–13] Using balanced homodyne detection (BHD),[14,15] a set of probability densities for the quadrature amplitude or phase are measured to yield a reconstructed Wigner distribution and density matrix for a single photon state of light.[16,17] In BHD, the single photon field and a strong coherent local oscillator field are overlapped at a 50/50 beam splitter, and the two interfered fields are detected and subtracted.[14] The single photon state mode matching to the local oscillator is a key factor that determines the efficiency of BHD and the shape of the Wigner function in phase-space, including temporal-mode and spatial-mode matchings.[18,19]

Due to several orders of magnitude light intensity difference, it is difficult to directly investigate the mode matching between a single photon state and a strong coherent local oscillator. In order to simplify the issue, temporal-mode matching is only considered when the single photon and the local oscillator interact at the single-mode fiber. In this article, by means of studying on the Hong–Ou–Mandel interference[20] between a heralded single photon and a coherent photon, attenuated from a local oscillator, in theoretical and experimental aspects, the principle of temporal-mode matching between the single photon state and the local oscillator is demonstrated. A multi-mode theoretical model of interference is given in Section 2, where the analytical expressions of the temporal-mode matching coefficient and the interference visibility are obtained. Experimental results of the relationship between the interference visibility and the temporal-mode matching coefficient are depicted in detail in Section 3. Finally, we discuss the implications and future directions for this work.

2. Theory

The schematic diagram of Hong–Ou–Mandel interference between a heralded single photon state and a coherent state is shown in Fig. 1. A train of pumped pulses is launched

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into a piece of $\chi^{(3)}$ nonlinear fiber, in which the spontaneous parametric process occurs and correlated photon pairs are generated when the phase-matching condition is satisfied. After passing a dual-band F2 spectral filter which is employed at the output of the fiber to separate the signal-idler photon pairs from the pump photons, the signal photons from the photon pairs serve as the trigger to herald the existence of the single photon in the idler band. When transmitting through a translation stage, the coherent photon is coupled with the heralded single photon at the beam splitter (BS) and an interference occurs. The signal photons are detected by a single photon detector SPD1, and the photons output from the BS are detected by SPD2 and SPD3, respectively.

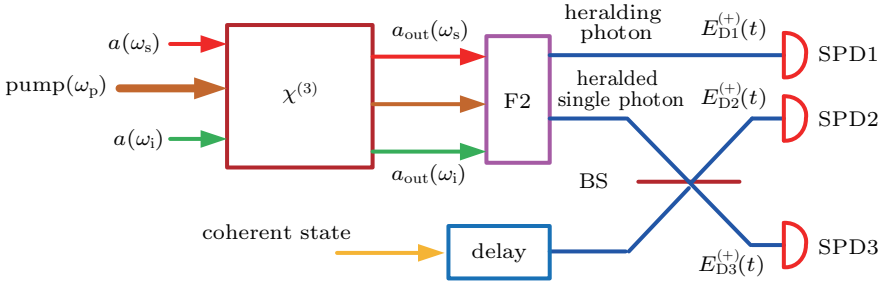


Fig. 1. (color online) Theoretical model of heralded single photon state interference with coherent state. ω_p, ω_s, and ω_i represent the frequencies of pump, signal, and idler photons, respectively. F2, dual-band filter; BS, beam splitter; delay, generating time delay $\delta\tau$; SPD, single photon detector.

When the central wavelength of the pump pulses is in the anomalous dispersion regime of the fiber, phase matching is satisfied and the probability of a spontaneous parametric process is significantly enhanced. The strong pump pulses with linear chirp C_p and Gaussian shaped spectrum can be written as

$$E_p^{(+)} = E_{p0}\,e^{-i\gamma P_p z}\int d\omega_p \exp\left\{-\frac{(\omega_p-\omega_{p0})^2(1+iC_p)}{2\sigma_p^2}\right\} \times e^{ik_p z - i\omega_p t}, \quad (1)$$

where E_{p0} and γ represent the amplitude of the pump field and the nonlinear coefficient of the fiber, respectively. ω_{p0}, σ_p, and C_p are the central frequency, bandwidth, and linear chirp of the pump, respectively. $P_p \propto \sigma_p^2 E_{p0}^2/\sqrt{1+C_p^2}$ is the peak power of the pump.

In the Heisenberg picture and in the low gain regime of the spontaneous parametric process, the field operator of the co-polarized signal (idler) beam at the output of the fiber is[21]

$$a_{out}(\omega_{s(i)}) \approx a(\omega_{s(i)}) + \frac{g\sqrt{1-iC_p}}{2\sqrt{\pi}\sigma_p} \times \int d\omega_{i(s)} F(\omega_{i(s)},\omega_{s(i)}) a^{\dagger}(\omega_{i(s)}), \quad (2)$$

where $g \propto \gamma P_p L$ is proportional to the gain of the spontaneous parametric process. $F(\omega_i,\omega_s)$ denotes the joint spectral amplitude, which can be written as[21]

$$F(\omega_i,\omega_s) = \exp\left\{-\frac{(\omega_i+\omega_s-2\omega_{p0})(1+iC_p)}{4\sigma_p^2} - \frac{1}{2}\left(\frac{\omega_i-\omega_{i0}}{A}+\frac{\omega_s-\omega_{s0}}{B}\right)\right\}, \quad (3)$$

where ω_{i0} and ω_{s0} are the central frequencies of the signal and idler beams, respectively, and satisfy $2\omega_{p0}=\omega_{i0}+\omega_{s0}$. A and B are proportional to the bandwidth of the phase matching function in idler and signal bands, respectively, which play a significant role in controlling the two-photon spectral property.[21]

The signal and idler photons are filtered out by dual-band filters F2, respectively, which can be described as

$$E_{s(i)}^{(+)} = \frac{\sqrt{\eta_{s(i)}}}{\sqrt{2\pi}}\int d\omega_{s(i)} f_{s(i)}(\omega_{s(i)}) a_{out}(\omega_{s(i)})\, e^{-i\omega_{s(i)}t}, \quad (4)$$

where $\eta_{s(i)}$ is the transmission efficiency in the signal (idler) band. The function $f_{s(i)}(\omega_{s(i)})$ represents the spectrum of filter F2 in the signal (idler) band

$$f_{s(i)}(\omega_{s(i)}) = \exp\left\{-\frac{(\omega_{s(i)}-\omega_{s(i)0})^2}{2\sigma_{s(i)}^2} - \frac{ik''_{s(i)}d_{s(i)}(\omega_{s(i)}-\omega_{s(i)0})^2}{2}\right\}, \quad (5)$$

where $\sigma_{s(i)}$ is the bandwidth of filter F2 in the signal (idler) band. $k''_{s(i)}$ and $d_{s(i)}$ are the second order dispersion coefficient and the length of the transmission medium in the signal (idler) band, respectively.

The coherent state can be treated as a classical field

$$E_c^{(+)}(t) = \frac{\sqrt{\eta_c}E_{c0}}{\sqrt{2\pi}}\int d\omega_c \exp\left\{-\frac{(\omega_c-\omega_{c0})^2(1+iC_c)}{2\sigma_c^2}\right\}, \quad (6)$$

where $|E_{c0}|$, σ_c, and C_c are the amplitude, bandwidth, and chirp of the coherent field, respectively, and $|E_{c0}| \ll 1$. Here, we assume that the central frequency of the coherent state, ω_{c0}, is equal to the central frequency of the heralded single photon state, ω_{i0}.

The signal field serving as the trigger is detected by SPD1

$$E_{D1}^{(+)}(t) = \sqrt{\eta_{D1}}E_s^{(+)}(t), \quad (7)$$

where η_{D1} is the quantum efficiency of SPD1. The output fields of the beam splitter are detected by SPD2 and SPD3, respectively,

$$E_{D2}^{(+)}(t) = \sqrt{\eta_{D2}}[\sqrt{T}E_{i}^{(+)}(t) + i\sqrt{R}E_{c}^{(+)}(t+\delta\tau)], \quad (8)$$

$$E_{D3}^{(+)}(t) = \sqrt{\eta_{D3}}[i\sqrt{R}E_{i}^{(+)}(t) + \sqrt{T}E_{c}^{(+)}(t+\delta\tau)], \quad (9)$$

where η_{D2} and η_{D3} are the quantum efficiencies of SPD2 and SPD3, respectively. T and R represent the transmissivity and reflectivity coefficients of the beam splitter, respectively. $\delta\tau$ denotes the relative delay between the coherent state and the heralded single photon state.

The triple coincidence rate of the three detectors is

$$P_{TC} = \int_{-\infty}^{\infty} dt_1\, dt_2\, dt_3 ||E_{D3}^{(+)}(t_3)E_{D2}^{(+)}(t_2)E_{D1}^{(+)}(t_1)|0\rangle||^2. \quad (10)$$

We first expand $E_{D3}^{(+)}(t_3)E_{D2}^{(+)}(t_2)E_{D1}^{(+)}(t_1)$ using Eqs. (7)–(9). According to the quantum form of the Gaussian moment-factoring theorem,[19,22] equation (10) is rewritten as the sum of five terms

$$\begin{aligned} P_{TC} &= \eta_{D1}\eta_{D2}\eta_{D3}[TRP_{sii} + TRP_s g_c^{(2)} P_c^2 + T^2\xi_i P_s P_c \\ &\quad + R^2\xi_i P_s P_c - 2TR\xi_i P_s P_c S' e^{-\delta\tau^2/x^2}]. \end{aligned} \quad (11)$$

The first term $P_{sii} = \int dt_1\, dt_2\, dt_3 ||E_i^{(+)}(t_3)E_i^{(+)}(t_2)E_s^{(+)}(t_1)|0\rangle||^2$ is the auto-correlation function of the heralded single photon field; when we assume the single photon field is ideal, P_{sii} is equal to 0.[9] The second term is the auto-correlation function of the coherent field $g_c^{(2)}P_c^2 = \int dt_1\, dt_2 ||E_c^{(+)}(t_2)E_c^{(+)}(t_1)|0\rangle||^2$ multiplied by the signal channel count rate $P_s = \int dt ||E_s^{(+)}(t)|0\rangle||^2$, where the normalized auto-correlation function of the coherent field $g_c^{(2)} = 1$.[23] The third and the fourth terms both represent the cross-correlation function of the heralded single photon field and the coherent field, and can be written as the product of $P_s\xi_i = \int dt_1\, dt_2 ||E_s^{(+)}(t_2)E_i^{(+)}(t_1)|0\rangle||^2$ and $P_c = \int dt ||E_c^{(+)}(t)|0\rangle||^2$, where $\xi_i = \sigma_i/\sqrt{\sigma_i^2 + \sigma_s^2 + 2\sigma_p^2}$ is the collection efficiency of the idler channel.[9] The last term represents the interference between the heralded single photon state and the coherent state, and S' is the temporal-mode matching coefficient of the two fields.

Finally, the expression of P_{TC} can be simplified to

$$\begin{aligned} P_{TC} &= \eta_{D1}\eta_{D2}\eta_{D3}P_s[TRP_c^2 + (T^2+R^2)\xi_i P_c \\ &\quad - 2TR\xi_i P_c S' e^{-\delta\tau^2/x^2}], \end{aligned} \quad (12)$$

where P_s is written as

$$P_s = \int dt ||E_s^{(+)}(t)|0\rangle||^2 = \frac{\eta_s|g|^2\sqrt{1+C_p^2}\sigma_s}{2\sqrt{2}\sigma_p}, \quad (13)$$

and $P_c = \int dt ||E_c^{(+)}(t)||^2$ is the detection rate of coherent photon.

The temporal-mode matching coefficient S' can be described as

$$S' = 2\left\{\sqrt{\left(\frac{\tau_c}{\tau_i'} + \frac{\tau_i'}{\tau_c}\right)\left\{\frac{\tau_c}{\tau_i'} + \frac{\tau_i'}{\tau_c}\left[1 + \frac{\sigma_i'^2}{\sigma_0^2}\left(\frac{1}{(g_s^{(2)}-1)^2} - 1\right)\right]\right\} + \frac{S_c'^2}{\tau_i'^2\tau_c^2}}\right\}^{1/2}, \quad (14)$$

where

$$g_s^{(2)} = \frac{\int dt_1\, dt_2 ||E_s^{(+)}(t_2)E_s^{(+)}(t_1)|0\rangle||^2}{\int dt ||E_s^{(+)}(t)|0\rangle||^2}$$

is the normalized auto-correlation function of the signal field[19,24] and

$$\sigma_0 = \sqrt{\frac{\sigma_s^2(1+2\sigma_p^2/B^2) + 2\sigma_p^2}{1 + 2\sigma_p^2/A^2 + \sigma_s^2(1/B - 1/A)^2}}$$

is the bandwidth of the idler photons correlated with the trigger photons. $\sigma_i' = \sigma_i\sigma_0/\sqrt{\sigma_0^2 + \sigma_i^2}$ represents the bandwidth of the heralded single photon field. $\tau_i' = 1/\sigma_i'$ and $\tau_c = 1/\sigma_c$ are the coherent time of the heralded single photon and the coherent photon, respectively. In addition, coefficient $x = 2/S'\sqrt{\sigma_i'^2 + \sigma_c^2}$, and the mode matching factor S_c' related to chirp is

$$S_c' = \frac{C_c}{\sigma_c^2} - k_i'' d_i - \frac{C_p[(1/A^2 - 1/(AB))\sigma_s^2 + 1]}{\sigma_s^2(1+2\sigma_p^2/A^2) + 2\sigma_p^2}. \quad (15)$$

According to the principle of Hong–Ou–Mandel interference and Eq. (12), the interference visibility of the heralded single photon and coherent photon, V, can be expressed as

$$V = \frac{P_{TC}(\infty) - P_{TC}(0)}{P_{TC}(\infty)} \approx \frac{S'}{\frac{T^2+R^2}{2TR} + \frac{P_c}{2\xi_i}}. \quad (16)$$

Equation (16) indicates the functional relationship between coefficient S' and visibility V. When the visibility of interference is experimentally acquired, we can derive the value of S' based on Eq. (16) and other experimental parameters.

In order to achieve the perfect temporal-mode matching between two fields ($S' \approx 1$), the following conditions should be satisfied. Firstly, the coherent time of the heralded single photon τ_i' is equal to the coherent time of the coherent photon τ_c. Secondly, the heralded single photon field should be in the single temporal-mode ($g_s^{(2)} = 2$),[24] which guarantees that $\frac{\sigma_i'^2}{\sigma_0^2}(\frac{1}{(g_s^{(2)}-1)^2} - 1)$ approaches to 0. Finally, the temporal

mode matching coefficient S'_c, induced by the linear chirp and second-order dispersion, is close to 0.

3. Experiment

The experimental setup of interference between the heralded single photon state and the coherent state is shown in Fig. 2. The heralded single photon state is generated by pulsed light pumping a piece of 300-m-long dispersion shifted fiber ($\lambda_0 \simeq 1538$ nm), which is immerged into liquid nitrogen to suppress the spontaneous Raman scattering photons.[25] The pump is a sequence of pulse train at 41 MHz rate, which is obtained by spatially dispersing the output of a fiber mode-locked laser (Pricisionphotonics, model PPC) with a diffraction grating. To achieve the required power, the pump pulses are amplified by an erbium-doped-fiber amplifier (EDFA). The full width at half maximum (FWHM) of 0.6 nm and 1538.2 nm central wavelength pump is obtained after the EDFA output passes through a tunable filter F1 (Newport, TBF-1550-1.0). A polarization beam splitter (PBS) is placed after the output port of the DSF. With proper adjustment of the fiber polarization controller (FPC), the signal and idler photons cross-polarized with the pump photons can be rejected.[25]

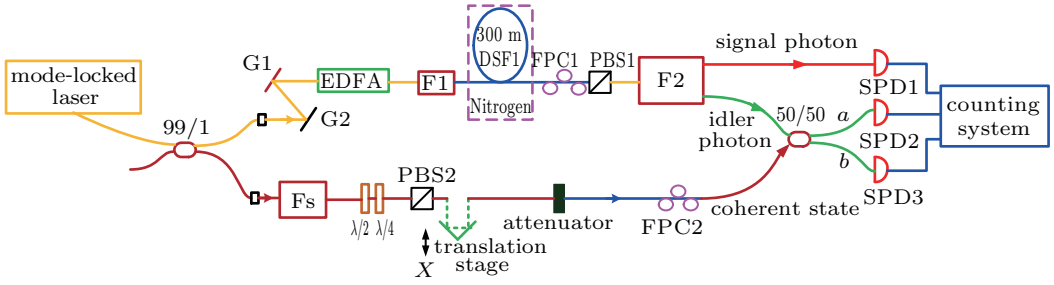


Fig. 2. (color online) Experimental setup of quantum interference between the heralded single photon state and the coherent state in optical fiber. G, grating; M, mirror; F, filter; PBS, polarization beam splitter; FPC, fiber polarization controller; SPD, single-photon detector.

To reliably detect the scattered photon-pairs, a pump to photon-pair rejection ratio in excess of 100 dB is required. The signal channel filter in F2 consists of a double-grating filter cascaded with a Bragg grating filter, where the central wavelength and the FWHM of the signal channel are 1544.5 nm and 0.14 nm, respectively. The idler channel filter in F2 consists of two cascaded WDM filters with the super-Gaussian shape spectrum, where the central wavelength and the FWHM of the idler channel are 1531.90 nm and 1.17 nm, respectively. Under this experimental condition, we can obtain the high collection efficiency[9] and the single temporal-mode heralded single photon state, where the FWHM of the heralded single photon state is fixed at 0.68 nm. The photon counting system consists of three single photon detectors SPD1 (Id Quantique, ID200), SPD2 (Princeton Lightwave, PLI-AGD-SC), and SPD3 (Princeton Lightwave, PGA-600) operated in a gated-Geiger mode, whose detection window widths are set at 2.5 ns, 1 ns, and 1 ns, respectively. The trigger frequency of the SPDs is about 2.581 MHz, which is 1/16 of the repetition rate of the pump pulses.

When the signal photons are detected by SPD1, the electric outputs herald the existence of single photons in the idler channel. After passing through the 50/50 fiber coupler, the idler photons are detected by SPD2 and SPD3, respectively. The quantum efficiencies and dark count probabilities of the three SPDs are 20%, 17%, 12% and 2.1×10^{-5}, 3.5×10^{-5}, 2.9×10^{-5}, respectively. The total detection efficiencies for the signal channel, idler channel a, and idler channel b are 2.3%, 3.2%, and 2.3%, respectively, when the transmission efficiency of DSF (73%), the transmission efficiencies of dual-band F2 in the signal band and idler band (15% and 50%), and other transmission components efficiency (about 90%) are considered.

In the Hong–Ou–Mandel interference scheme, 1% output port of 99/1 coupler is reshaped by filter Fs, so that the spectrum of the attenuated strong local oscillator (coherent state) is the same as that of the heralded single photon state. Before coupling to the 50/50 beam splitter, the coherent photon is delayed by the reflector mirrors mounted on a translation stage. We properly adjust the translation stage and the fiber polarization controller (FPC) to make the two fields overlap in spatial-temporal mode and polarization mode. In addition, to confirm the single temporal-mode of the heralded single photon field, we measure the normalized intensity correlation function $g_s^{(2)}$ for the individual signal photon and $g_s^{(2)} = 1.95 \pm 0.04$ is obtained.

When the heralded single photon and coherent photon are fed into the 50/50 beam splitter from two input ports, the observation of the interference between the two states is through measuring the triple coincidence count rate P_{TC} versus the position of the translation stage X. When the average pump power and the input coherent photon intensity are fixed at 150 μW and 0.04 photon/pulse, $57 \pm 10\%$ interference visibility is obtained. To reliably subtract the background pho-

tons, single, two-fold, and three-fold counts are recorded when only the single photon or coherent photon is presented in the input of the 50/50 beam splitter. After subtracting three-fold background coincidences of 57 counts/50 min from the original data, $82 \pm 11\%$ visibility of interference is shown in Fig. 3. Afterwards, a series of Hong–Ou–Mandel interference experiments are carried out with the intensity of the coherent state varied, of which the calculated temporal-mode matching coefficient S' is fixed at 0.988 and the visibility is shown in Fig. 4.

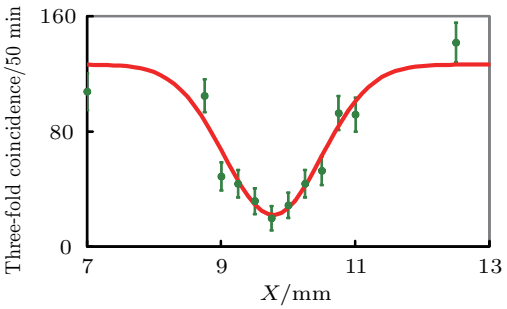


Fig. 3. (color online) Experimental result of quantum interference between heralded single photon and coherent state in optical fiber. The pattern of Hong–Ou–Mandel interference is represented by the relationship between three-fold coincidence counts versus the position of the translation stage, X, in the scheme, when the intensity of the coherent state P_c is fixed at 0.04 photon/pulse. After subtracting three-fold background coincidences of 57 counts/50 min from the original data, the visibility $82 \pm 11\%$ is obtained. Because of the small three-fold coincidence count, the relative statistical error of each data point is large, which causes the data points in the border to deviate a little from the theoretical curve.

Meanwhile, another group of Hong–Ou–Mandel interference curves is acquired at the condition of $S' = 0.777$, when the FWHMs of the pump, signal, idler, and coherent photons are changed to 0.6 nm, 1.12 nm, 1.17 nm, and 0.9 nm, respectively. Figure 4 shows a measurement on the interference visibility as a function of the intensity of the coherent state with different temporal-mode matching coefficients, where the blue diamonds ($S' = 0.988$) and the pink circles ($S' = 0.777$) are the experimental data. According to the experimental parameters and Eqs. (14)–(16), the blue and pink lines are also plotted as the theoretical curves of interference visibility corresponding to the blue diamonds and pink circles, respectively. We note that the observed visibility data are slightly lower than the theoretical curves. One reason is that the heralded single photons are contaminated by the spontaneous Raman scattering photons, although the $\chi^{(3)}$ fiber has been immerged into the liquid nitrogen. Another reason is that the correlated photon pairs filters F2 used in our schemes have super-Gaussian shape, while the filters F2 in the theory model are assumed to be Gaussian shaped.

In our experiment, the interference visibility between the heralded single photon state and the coherent state is related to the intensity of the coherent photon, and more importantly, it also informs the degree of temporal-mode matching between the two states. In addition, the low coincidence count rates for recording interference, limited by the trigger frequency of SPDs in the scheme, could be improved in future work by using high-performance single photon detectors with working frequency well over 100 MHz.[26] A superconducting single photon detector is a better alternative for improving the coincidence count rate, whose working frequency can reach several GHz and the dark count rate is even lower.[27]

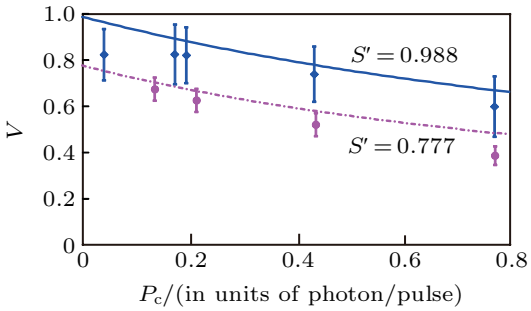


Fig. 4. (color online) The interference visibility V versus the coherent state intensity P_c with different temporal-mode matching coefficients. The blue diamonds are experimental data obtained when the FWHMs of the pump, signal, idler, and coherent photons are 0.6 nm, 0.14 nm, 1.17 nm, and 0.69 nm, respectively, corresponding to the parameters σ_p, σ_s, σ_i, and σ_c of 0.282 TRad, 0.062 TRad, 0.564 TRad, and 0.332 TRad, other parameters $k_i'' = -24$ ps^2/km, $d_i = 5$ m, $C_p = 0.4$, $C_c = 0.51$, calculated $S_c' = 2.29$, $S' = 0.988$; the pink solid circles are experimental data obtained when the FWHMs of the pump, signal, idler, and coherent photons are 0.6 nm, 1.12 nm, 1.17 nm, and 0.9 nm, respectively, corresponding to the parameters σ_p, σ_s, σ_i, and σ_c of 0.282 TRad, 0.53 TRad, 0.564 TRad, and 0.434 TRad, other parameters $k_i'' = -24$ ps^2/km, $d_i = 5$ m, $C_p = 0.4$, $C_c = 0.35$, calculated $S_c' = 5.10$, $S' = 0.777$. The solid-blue and dash-dotted pink lines are the theoretical curves using experimental parameters.

4. Conclusion

In summary, we demonstrate the Hong–Ou–Mandel interference of the heralded single photon and coherent photon in an optical fiber and find the visibility revealing the temporal-mode matching of the two types of photons. We discuss the main experimental factors that influence the temporal-mode coefficient in the scheme. The technique we reported can be used to obtain the temporal-mode matching degree between a single photon and the strong local oscillator field in BHD systems, which is beneficial for an accurate tomographic reconstruction of the single-photon Fock state in the quantum optics field.[16,17]

References

[1] Stucki D, Gisin N, Guinnard O, Ribordy G and Zbinden H 2002 *New J. Phys.* **4** 41
[2] Mi J L, Wang F Q, Lin Q Q and Liang R S 2008 *Chin. Phys. B* **17** 1178
[3] Chen J J, Han Z F, Zhao Y B, Gui Y Z and Guo G C 2006 *Physics* **35** 785
[4] Knill E, Laflamme R and Milburn G J 2001 *Nature* **409** 46
[5] Bouwmeester D, Pan J W, Mattle K, Eibl M, Weinfurter H and Zeilinger A 1997 *Nature* **390** 575

[6] Hong C K and Mandel L 1986 *Phys. Rev. Lett.* **56** 58
[7] Lounis B and Orrit M 2005 *Rep. Prog. Phys.* **68** 1129
[8] Pittman T B, Jacobs B C and Franson J D 2005 *Opt. Commun.* **246** 545
[9] Yang L, Ma X X, Guo X S, Cui L and Li X Y 2011 *Phys. Rev. A* **83** 053843
[10] Lvovsky A I, Hansen H, Aichele T, Benson O, Mlynek J and Schiller S 2001 *Phys. Rev. Lett.* **87** 050402
[11] Burch E T, Henelsmith C, Larson W and Beck M 2015 *Phys. Rev. A* **92** 032328
[12] Bimbard E, Boddeda R, Vitrant N, Grankin A, Parigi V, Stanojevic J, Ourjoumtsev A and Grangier P 2014 *Phys. Rev. Lett.* **112** 033601
[13] Wang J C, Liu S T and Wang Y Y 2010 *Chin. Phys. B* **19** 074206
[14] Shapiro J H 1985 *IEEE J. Quantum Elect.* **QE-21** 237
[15] Zavatta A, Bellini M, Ramazza P L, Marin F and Arecchi F T 2002 *J. Opt. Soc. Am. B* **19** 1189
[16] Leonhardt U 1995 *Phys. Rev. Lett.* **74** 4101
[17] Lvovsky A I and Raymer M G 2009 *Rev. Mod. Phys.* **81** 299
[18] Banaszek K and Wodkiewicz K 1997 *Phys. Rev. A* **55** 3117
[19] Ma X X, Cui L and Li X Y 2015 *J. Opt. Soc. Am. B* **32** 946
[20] Hong C K, Ou Z Y and Mandel L 1987 *Phys. Rev. Lett.* **59** 2044
[21] Ma X X, Li X Y, Cui L, Guo X S and Yang L 2011 *Phys. Rev. A* **84** 023829
[22] Caves C M 1982 *Phys. Rev. D* **26** 1817
[23] Glauber R J 1963 *Phys. Rev.* **130** 2529
[24] Ou Z Y, Rhee J K and Wang L J 1999 *Phys. Rev. A* **60** 593
[25] Yang L, Li X Y and Wang B S 2008 *Acta Phys. Sin.* **57** 4933 (in Chinese)
[26] Jian Y, Wu E, Wu G and Zeng H P 2010 *IEEE Photon. Tech. Lett.* **22** 173
[27] Natarajan C M, Tanner and Hadfield R H 2012 *Supercond. Sci. Tech.* **25** 63001