

Two-photon interference between an independent laser and single photons with ultralong coherence time

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Two-photon interference (TPI) underpins many photonic quantum technologies and is commonly regarded as a quantum effect requiring indistinguishable photons. Here, we demonstrate TPI between single photons with ultralong coherence time and an independent continuous-wave laser. The measurements reveal a sharp antibunching dip, governed by the single-photon correlation time, together with a broad Hong-Ou-Mandel dip whose half-width is set by the mutual coherence time of the two sources. We achieve a maximum TPI visibility of $72 \pm 2\%$, well above the 50% classical limit, thereby confirming the quantum nature of TPI. At the same time, we observe a broad visibility background and a beat visibility below 50%, signatures of classical interference. Both quantum and classical visibility features remain unchanged for frequency separations up to 10^4 times the linewidth of the single photons, showing no distinction between distinguishable and indistinguishable photons. By applying both general wave superposition theory and a quantum field approach, we derive the same cross-correlation functions that quantitatively reproduce the data. Our results show that quantum and classical features of TPI originate from the same underlying fourth-order interference process arising from second-order interference within the mutual coherence time. Photon indistinguishability is a sufficient condition for TPI to occur, but not a necessary one. This insight offers different perspectives for the development of quantum photonic technologies based on independent photons.

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I. INTRODUCTION

Two-photon interference (TPI), particularly in the form of Hong-Ou-Mandel (HOM) interference [1,2], is a cornerstone phenomenon in quantum optics with widespread applications in quantum information science and technology. When two identical photons—matched in frequency, polarization, spatial, and temporal modes—are simultaneously directed into a 50:50 beam splitter from different input ports, they exhibit photon bunching and emerge together from the same output port. It is commonly believed that the indistinguishability of identical photons leads to maximum TPI and thus maximum photon bunching attributed to the bosonic nature of light [3–5]. This insight has driven extensive research into the generation of indistinguishable photons from both single emitters [6–11] and independent or dissimilar sources [12–18]. Such

capabilities are central to a broad spectrum of quantum technologies, including photonic quantum computing [19–23], quantum communication [24–29], quantum sensing [30], and quantum metrology [31,32].

Since the original HOM experiment, TPI involving distinguishable entangled photons has been demonstrated [33,34], establishing that TPI arises from the coherent superposition of two-photon amplitudes. Recently, interest has shifted to TPI between nonentangled photons from independent sources, where the photons are distinguishable in frequency or other degrees of freedom [35–39]. In these experiments, the frequency separation between photons exceeds their linewidths by factors of 8.6 times [35], 16 times [36,38], and 1.8 times [39], yet TPI is still observed. It has been suggested that while photon indistinguishability may not be strictly required at the beam splitter, it is necessary at the detectors that erase the distinguishing information of the photons [36,39]. More recently, Jones *et al.* [40] reported multiparticle interference between pairwise distinguishable photons, where the detection process did not erase distinguishing information. In addition to these findings, Seron *et al.* [41] discovered that bosonic bunching in a multimode interferometer is not maximized by indistinguishable photons, indicating that photon bunching is not equivalent to photon indistinguishability.

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In this study, we report on time-resolved TPI experiments between single photons with ultralong coherence time and an independent laser. We vary the frequency difference between the two sources from being indistinguishable to spectrally distinguishable, achieving frequency separations up to 10^4 times the linewidth of single photons (<100 kHz). Previous TPI studies [6–17] have primarily focused on photons with short coherence times, limited by the radiative lifetime of their emitters. This constraint complicates the separation of TPI effects from intrinsic single-photon correlations. Here, by using single photons generated from a resonantly driven QD coupled to an optical microcavity operating in the Purcell regime [42], we coherently convert the driving laser into single photons that retain laser's long coherence time (>10 μ s)—five orders of magnitude longer than the photon correlation time. This allows us to clearly distinguish TPI from single-photon characteristics.

When the photons are indistinguishable, we observe a sharp antibunching dip with a maximum TPI visibility of $72 \pm 2\%$, surpassing the classical threshold of 50% and confirming quantum interference between the laser and single photons, consistent with earlier work using spontaneous parametric down-conversion sources [43]. In addition, we identify a broad interference background and a beat visibility below 50%, characteristic of classical interference effects [2,44]. These interference features remain robust across all tested frequency separations below the inverse detector resolution and are insensitive to photon distinguishability.

To interpret these observations, we employ both wave superposition theory and a quantum field approach and derive the identical cross-correlation functions that quantitatively reproduce the experimental data. From this analysis, three key insights emerge: (1) quantum and classical features of TPI stem from the same underlying interference process; (2) TPI between independent photons constitutes a fourth-order temporal interference effect that originates from second-order interference within the mutual coherence time; and (3) while photon indistinguishability is sufficient for TPI, it is not necessary, as TPI can also occur between photons of different frequencies.

II. SINGLE PHOTONS WITH ULTRALONG COHERENCE TIME

In contrast to single-sided cavity geometries commonly employed in emission-based single-photon sources [6–11], we study a symmetric double-sided cavity resonantly coupled to a single QD in the Purcell regime. The system is characterized by a high cooperativity $C = 2g^2/(\kappa\gamma_{\perp}) \gg 1$ and a small critical photon number $n_0 = \gamma_{\perp}\gamma_{\parallel}/(4g^2) \ll 1$, where g is the QD-cavity interaction strength, κ is the cavity photon decay rate, $\gamma_{\parallel}$ is the QD spontaneous emission rate into non-cavity modes, and $\gamma_{\perp} = \gamma_{\parallel}/2 + \gamma^*$ is the total decoherence rate, including the pure dephasing rate γ^* . The cooperativity quantifies that the QD emission rate into the cavity mode is C times higher than that into the leaky modes, provided that the pure dephasing rate is negligible. The critical photon number describes the number of cavity photons required to saturate the QD response. Our cavity design enables deterministic light-matter interaction, cavity-enhanced coherent scattering, and

strong optical nonlinearity at the single-QD, single-photon level. In the Purcell regime, the cavity quantum electrodynamics (CQED) system can also be treated as an effective two-level system with a modified emission rate, an approximation valid under weak driving where the QD remains far from saturation. In the weak-driving regime, resonance fluorescence is dominated by coherent scattering, manifested as reflection.

The QDs are embedded at the center of a λ -thick GaAs cavity ($\lambda = 920$ nm) sandwiched between 30 (18) pairs of bottom (top) GaAs/Al_{0.9}Ga_{0.1}As distributed Bragg reflectors (DBRs). Transverse confinement is provided by index guiding in micropillars. To achieve an effectively symmetric double-sided cavity, the two DBRs are designed with intentional asymmetry such that leakage through the top mirror balances losses from the bottom mirror, sidewalls, and background absorption. Further details regarding sample growth, device fabrication, and characterization—including reflection, exciton lifetimes, Purcell factor and coherence times—are given in our recent work [42]. The relevant CQED parameters are $g/2\pi = 4.7$ GHz, $\kappa/2\pi = 36.8$ GHz, $\gamma_{\parallel}/2\pi = 0.35$ GHz, and $\gamma^*/2\pi \simeq 0$ GHz, yielding a cooperativity $C = 6.9$ and a critical photon number is $n_0 = 6.9 \times 10^{-4}$. Throughout this work, we characterize the driving power using saturation parameter $S = 2(\Omega/\Gamma_{\parallel})^2$, where Ω is the Rabi frequency and $\Gamma_{\parallel} = 4g^2/\kappa + \gamma_{\parallel}$ is the cavity-enhanced QD emission rate, which is $\Gamma_{\parallel}/2\pi = 2.8$ GHz.

The sample is mounted in a closed-cycle cryostat (Fig. 1), and the QD transition is tuned into resonance with the cavity mode by adjusting the temperature to $T = 14.9$ K. A continuous-wave tunable Ti:sapphire laser (M Squared) with a linewidth below 100 kHz (specified over a 100 μ s measurement interval) is used to resonantly drive the cavity. Photon detection is performed using superconducting nanowire single-photon detectors (SNSPDs) featuring a nominal timing resolution of 20 ps and a detection efficiency $\geq 85\%$ at 900 nm, close to the QD transition wavelength. These specifications provide sufficient temporal resolution and efficiency for exciton lifetime and time-resolved TPI measurements.

By tuning the excitation laser into resonance with the QD, we measure the second-order autocorrelation function of the reflected light using a Hanbury Brown-Twiss setup. At low driving power ($S = 0.01$, Heitler regime), we obtain $g^{(2)}(0) = 0.030 \pm 0.002$ [Fig. 2(a)], indicating high-single-photon purity. The single-photon antibunching dip has a half-width of 115 ps, which is twice the cavity-enhanced QD exciton lifetime (57 ps) [42]. The reflected signal consists of the reflected driving field superimposed with the cavity output field [42]: The former exhibits Poissonian statistics, while the latter displays superbunching originating from photon-induced tunneling [45,46] and multiphoton scattering [47]. This reveals that the conventional picture—where a single QD is assumed to scatter or emit only one photon at a time—breaks down at low driving powers. In particular, the observed antibunching does not arise from spontaneous emission. Instead, it results from complete destructive interference between the reflected driving field and the cavity output, which cancels the two-photon probability amplitude [48] and thereby converts the driving laser field into single photons [42]. This interference-

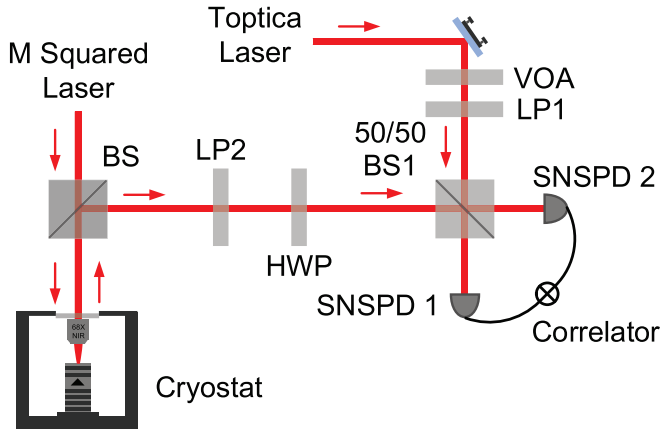


FIG. 1. Experimental setup for single-photon generation and time-resolved TPI measurements between single photons and an independent laser (Toptica CTL-950) using an HOM interferometer. Single photons with ultralong coherence time are generated from a QD in an optical microcavity under weak resonant excitation by a continuous-wave tunable Ti:sapphire laser (M Squared, linewidth <100 kHz). The sample is kept at cryogenic temperature in a closed-cycle cryostat (attocube attoDry 800). For TPI, linear polarizers LP1 and LP2 are set in parallel, and a half-wave plate (HWP) is used to switch between parallel and cross-polarization configurations. Correlation measurements are recorded with an eight-channel time-correlated single-photon counter (Swabian Instruments, timing jitter 3 ps). BS and BS₁: beam splitters; LP1 and LP2: linear polarizers; HWP: half-wave plate; VOA: variable optical attenuator; SNSPD1 and SNSPD2: superconducting nano-wire single-photon detectors (Scontel, time resolution 20 ps and detection efficiency $\geq 85\%$ at 900 nm).

based mechanism is consistent with the picture of resonance fluorescence proposed four decades ago [49] and recently confirmed experimentally [50].

Figure 2(b) presents the degree of first-order coherence $g^{(1)}(\tau)$ of the reflected light versus time delay measured with a Mach-Zehnder interferometer at different driving powers (indicated by the saturation parameter S). At intermediate driving fields, we observe two distinct coherence times. The short 115-ps coherence time—twice the cavity-enhanced QD exciton lifetime (57 ps)—arises from two-photon and multiphoton scattering processes, which manifest as an incoherent component [42]. The long coherence time is attributed to the driving laser, which has a manufacturer-specified coherence time over $10 \mu\text{s}$. The incoherent scattering reduces the degree of first-order coherence. As the driving strength increases, the intensity ratio of the coherent to incoherent scattering decreases, leading to a decrease in the degree of first-order coherence. The experimental results (dots) align closely with the theoretical curves (solid lines) using the master equation [42].

III. TPI EXPERIMENTS

In the TPI experiments, the excitation is maintained in the Heitler regime with a fixed saturation parameter of $S = 0.01$, ensuring coherent scattering dominates. The reflected light exhibits both high single-photon purity [Fig. 2(a)] and an ultralong coherence time exceeding $10 \mu\text{s}$ [Fig. 2(b)],

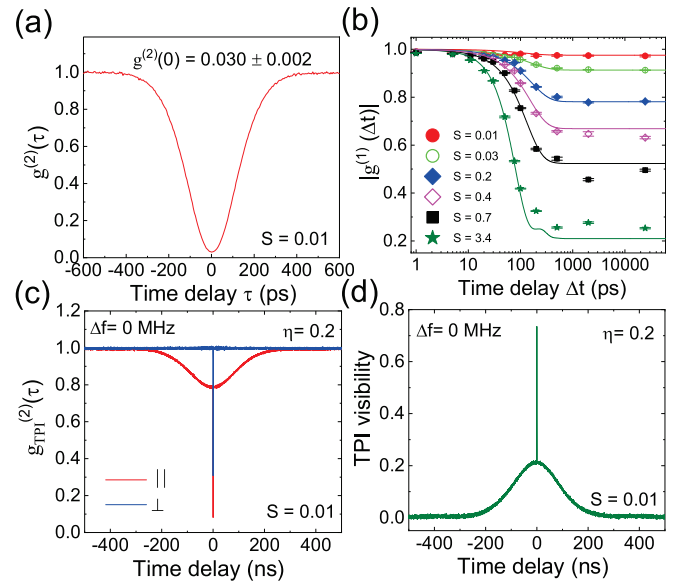


FIG. 2. Characterization of single photons with ultralong coherence time and TPI with an independent laser. (a) Second-order autocorrelation $g^{(2)}(\tau)$ of the reflected light measured with a Hanbury Brown-Twiss setup. The excitation laser is resonant with the QD, yielding $g^{(2)}(0) = 0.030 \pm 0.002$ at low driving power ($S = 0.01$, Heitler regime). (b) Degree of first-order coherence $g^{(1)}(\tau)$ measured with a Mach-Zehnder interferometer at different driving powers. Error bars represent the standard deviation from repeated measurements. Solid lines show master-equation simulations [42]. (c) Polarization-resolved second-order cross-correlations $g_{\text{TPI},\parallel}^{(2)}(\tau)$ and $g_{\text{TPI},\perp}^{(2)}(\tau)$ obtained with the HOM interferometer in Fig. 1. (d) Extracted TPI visibility as a function of time delay. In panels (c) and (d), the driving power is fixed at $S = 0.01$, the frequency detuning between the laser and single photons is set to $\Delta f = 0$ MHz and the laser-to-single-photon intensity ratio is $\eta = 0.2$.

corresponding to a photon linewidth below $4.1 \times 10^{-5} \mu\text{eV}$. This linewidth is six orders of magnitude narrower than the cavity-enhanced QD exciton linewidth $\Gamma_{\parallel}/2\pi = 11.5 \mu\text{eV}$, and five orders of magnitude narrower than the natural linewidth $\gamma_{\parallel}/2\pi = 1.4 \mu\text{eV}$ of the QD without cavity coupling [42]. While subnatural linewidth single photons in the Heitler regime have been reported [51–53], simultaneously achieving such narrow linewidths together with genuine single-photon characteristics has been considered unattainable [54,55].

A second continuous-wave tunable laser (Toptica CTL-950) is used to interfere with the single photons generated by the Ti:sapphire laser (M Squared), as illustrated in Fig. 1. The two lasers operate independently. Figure 2(c) displays the measured cross-correlation functions $g_{\text{TPI},\perp}^{(2)}(\tau)$ and $g_{\text{TPI},\parallel}^{(2)}(\tau)$ in cross- and parallel-polarization configurations. The two sources are tuned to the same frequency, making the photons from the Toptica laser and the single photons spectrally indistinguishable.

In the cross-polarization configuration, no interference is expected. Nevertheless, we observe a sharp antibunching dip at $\tau = 0$ with a half-width of 115 ps [Fig. 2(c), blue line], reflecting the single-photon character of the single photons reflected from the QD-cavity system.

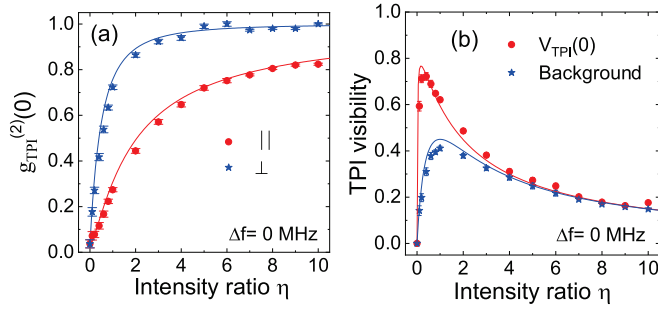


FIG. 3. Dependence of TPI measurements on the laser-to-single-photon intensity ratio η . (a) Zero-delay cross-correlations $g_{\text{TPI},\perp}^{(2)}(0)$ and $g_{\text{TPI},\parallel}^{(2)}(0)$ as functions of η . (b) Zero-delay TPI visibility $V_{\text{TPI}}(0)$ and maximum background visibility vs η . Error bars represent the standard deviation from repeated measurements. Experimental data (dots) are compared with calculations from Eqs. (1)–(3) (solid lines). In both panels, the driving power is fixed at $S = 0.01$ and the frequency detuning between laser and single photons is set to $\Delta f = 0$ MHz.

In the parallel-polarization configuration, in addition to the sharp single-photon dip, a broad dip at $\tau = 0$ with a half-width of 150 ns appears [see Fig. 2(c), red line]. This broad feature corresponds to the HOM dip [1,2], with its width set by the mutual coherence time between the Toptica laser and the single photons. From this measurement, we extract a mutual coherence time of 150 ns, consistent with the coherence time of the Toptica laser. By contrast, the single photons generated by the Ti:sapphire laser (M Squared) exhibit a much longer coherence time, exceeding 10 μs specified by the manufacturer.

In addition to the broad HOM dip, TPI shifts the sharp single-photon dip downward by the depth of the HOM dip [see Fig. 2(c)]. The TPI visibility is typically defined as $V_{\text{TPI}}(\tau) = [g_{\text{TPI},\perp}^{(2)}(\tau) - g_{\text{TPI},\parallel}^{(2)}(\tau)]/g_{\text{TPI},\perp}^{(2)}(\tau)$ [6–18]. From this, we extract a maximum visibility of $V_{\text{TPI}}(0) = 72 \pm 2\%$ [Fig. 2(d)], well above the classical limit of 50%, confirming the quantum nature of TPI. Meanwhile, the broad visibility background, with a maximum value of less than $22 \pm 1\%$, reflects the classical aspect of TPI.

Figure 3 displays $g_{\text{TPI},\perp}^{(2)}(0)$, $g_{\text{TPI},\parallel}^{(2)}(0)$, and $V_{\text{TPI}}(0)$ as functions of the laser-to-single-photon intensity ratio η . To analyze these results, we apply both general wave superposition theory and a quantum field approach, which yield identical second-order cross-correlation functions for TPI between laser light and single photons. The full derivation is provided in the Supplemental Material [Eqs. (S5), (S6), (S15), and (S16)] [56]. In the cross-polarization configuration, we obtain

$$g_{\text{TPI},\perp}^{(2)}(\tau) = \frac{1}{N} \{ \eta^2 R T g_L^{(2)}(\tau) + R T g_{\text{SP}}^{(2)}(\tau) + \eta(R^2 + T^2) \}, \quad (1)$$

and in the parallel-polarization configuration,

$$g_{\text{TPI},\parallel}^{(2)}(\tau) = \frac{1}{N} \{ \eta^2 R T g_L^{(2)}(\tau) + R T g_{\text{SP}}^{(2)}(\tau) + \eta(R^2 + T^2) - 2\eta R T V_0 |g_L^{(1)}(\tau)| |g_{\text{SP}}^{(1)}(\tau)| \cos(2\pi \Delta f \tau) \}, \quad (2)$$

where $N = (1 + \eta^2) R T + \eta(R^2 + T^2)$ is the normalization factor, $\eta = I_{\text{laser}}/I_{\text{SP}}$ is the laser-to-single-photon intensity

ratio, and $R = T = 50\%$ are the reflection and transmission coefficients of BS1 (see Fig. 1). The parameter V_0 accounts for mode overlap at BS1. $g_L^{(2)}(\tau) = 1$ and $g_{\text{SP}}^{(2)}(\tau)$ are the second-order auto-correlation functions of laser light and single photons, respectively. The first-order coherence functions are given by $g_L^{(1)}(\tau) = \exp(-|\tau|/\tau_L)$ and $g_{\text{SP}}^{(1)}(\tau) = \exp(-|\tau|/\tau_{\text{SP}})$, with coherence times $\tau_L = 150$ ns (Toptica laser) and $\tau_{\text{SP}} > 10 \mu\text{s}$ (single photons).

A coincidence event corresponds to two photons being detected by separate detectors. The first term in Eqs. (1) and (2) represents the coincidence events for both photons originating from the Toptica laser. The second term accounts for the coincidence events where both photons come from single photons. The third term includes the coincidence events for one photon from the Toptica laser and one from single photons. The fourth term in Eq. (2) is the only interference contribution, arising from TPI between one photon from the Toptica laser and one from the single photons. This interference produces the broad HOM dip observed in Fig. 2(c), with a half-width determined by the mutual coherence time of the two sources. As a fourth-order interference effect [2], TPI originates from second-order interference between photons within their mutual coherence time (see Secs. I and II of the Supplemental Material [56]). The calculated results from Eqs. (1) and (2) show good agreement with the experimental data in Fig. 3(a), yielding a fitted mode overlap of $V_0 = 0.85$.

From Eqs. (1) and (2), the TPI visibility is obtained as

$$V_{\text{TPI}}(\tau) = \frac{g_{\text{TPI},\perp}^{(2)}(\tau) - g_{\text{TPI},\parallel}^{(2)}(\tau)}{g_{\text{TPI},\perp}^{(2)}(\tau)} = \frac{2\eta V_0 e^{-|\tau|/\tau_L} \cos(2\pi \Delta f \tau)}{\eta^2 + 2\eta + g_{\text{SP}}^{(2)}(\tau)}. \quad (3)$$

The calculated visibilities based on Eq. (3) reproduce the experimental results in Fig. 3(b), capturing both the peak value and the background. According to Eq. (3), the maximum zero-delay visibility is expected at $\eta = \sqrt{g_{\text{SP}}^{(2)}(0)} = 0.17$, given $g_{\text{SP}}^{(2)}(0) = 0.03$. In contrast, the maximum background visibility is predicted at $\eta = 1$. Both predictions are confirmed by the data in Fig. 3(b). Finally, Eq. (3) indicates that unit visibility can, in principle, be achieved at $\eta = 0$ with $g_{\text{SP}}^{(2)}(0) = 0$, consistent with earlier work [43]. Importantly, Eq. (3) also shows that the TPI visibility $V_{\text{TPI}}(0)$ is independent of the frequency separation between the laser and single photons, provided the detectors are infinitely fast.

Based on the derivation of Eqs. (1) and (2) in the Supplemental Material [56], together with the close agreement between experiment and theory, we conclude that TPI between independent photons—formally a fourth-order interference—arises from second-order interference within the mutual coherence time. Crucially, photon indistinguishability is not a necessary condition. Indeed, TPI persists even for independent, distinguishable photons, as shown in Fig. 4 and the magnified views in Fig. 5. When the frequency separation between laser and single photons is varied over several orders of magnitude (up to 10^4 times larger than the single-photon linewidth, < 100 kHz), both the peak visibility $V_{\text{TPI}}(0)$ and the background (beat) visibility [Figs. 4(g) and 4(h)] remain unchanged from the indistinguishable case.

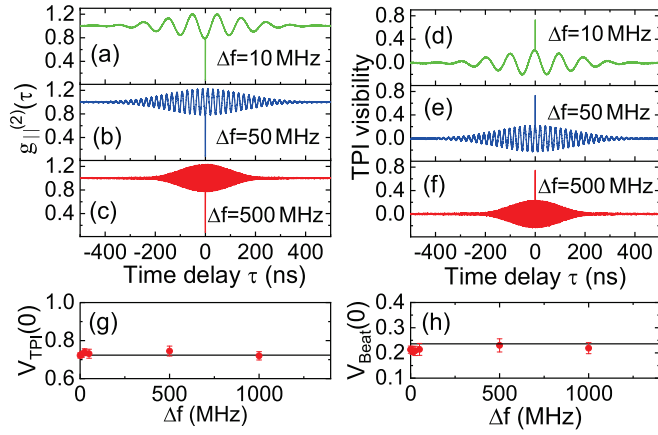


FIG. 4. Measured cross-correlations $g_{\text{TPI},||}^{(2)}(\tau)$ at frequency separations of (a) 10 MHz, (b) 50 MHz, and (c) 500 MHz. Corresponding TPI visibilities $V_{\text{TPI}}(\tau)$ are shown in panels (d)–(f). (g) Zero-delay TPI visibility $V_{\text{TPI}}(0)$ and (h) maximum background (beat) visibility as functions of frequency separation. Error bars represent the standard deviation from repeated measurements. Experimental data (red dots) are compared with calculations from Eq. (3) (solid lines). In all panels, the driving power is fixed at $S = 0.01$ and the laser-to-single-photon intensity ratio at $\eta = 0.2$.

A long photon coherence time and fast detector response are both essential for observing these effects. Coherent photons of different frequencies in the same spatial mode can interfere because their temporally extended, phase-stable wave packets overlap despite spectral distinguishability. The long coherence time ensures a slowly varying relative phase, while the fast detector response resolves the beat-frequency fringes arising from detuning, thereby avoiding temporal averaging due to jitter and preserving both TPI and beat visibilities. When the frequency separation between the laser and single photons exceeds the inverse detector resolution

[57], the beat fringes—though still present—can no longer be resolved, resulting in a simultaneous reduction of both TPI and beat visibilities (Fig. 5).

IV. CONCLUSIONS AND OUTLOOK

In summary, we have demonstrated TPI between single photons with ultralong coherence time and an independent laser, achieving frequency separations up to 10^4 times the single-photon linewidth—the highest ratio reported to date. Using a quantum dot coupled to a double-sided microcavity in the Purcell regime, we coherently convert the driving laser into single photons with coherence time exceeding 10 μs . The measurements reveal a sharp antibunching dip set by the single-photon correlation time and a broad HOM dip whose half-width is determined by the mutual coherence time of the two sources. We obtain a maximum TPI visibility of $72 \pm 2\%$, surpassing the 50% classical threshold and confirming the quantum nature of TPI, while a broad visibility background and a beat visibility below 50% reveal the accompanying classical feature. These signatures persist across all tested frequency separations below the inverse detector resolution, with no distinction between indistinguishable and distinguishable photons. A theoretical analysis based on both wave superposition and quantum field approaches reveals that TPI between independent photons—formally a fourth-order effect—arises from second-order temporal interference within the mutual coherence time. Thus, photon indistinguishability is a sufficient but not necessary condition for TPI.

The maximum TPI visibility of $72 \pm 2\%$ achieved here is limited primarily by the mode mismatch between the two different lasers. Further improvement is possible by employing mode-matched sources, such as photons derived from the same laser [58].

These results broaden the fundamental understanding of TPI and open further opportunities for quantum photonic technologies. In particular, our approach offers a pathway to interface weak coherent lasers—widely used in quantum key distribution (QKD)—with single-photon sources, a key ingredient for quantum state transfer, quantum relays [59], quantum repeaters, and quantum memories in the emerging quantum internet [24,25,27]. Beyond networking, ultralong-coherence single photons may also enable advances in quantum sensing [30] and in interference-based photonic quantum technologies, such as mode-pairing and asynchronous measurement-device-independent QKD [60–65].

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DATA AVAILABILITY

No data were created or analyzed in this study.

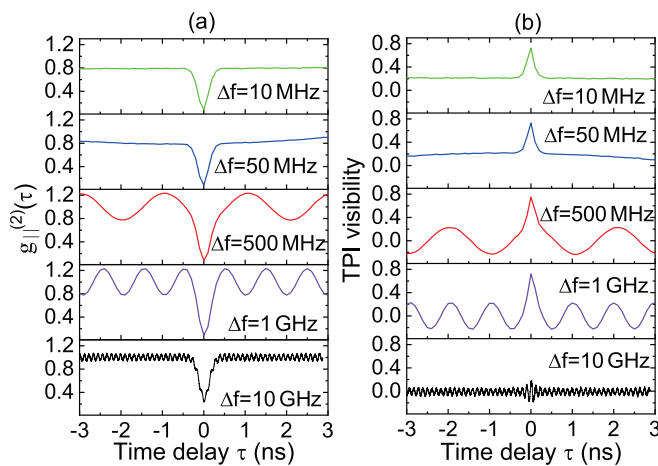


FIG. 5. Enlarged views of (a) $g_{\text{TPI},||}^{(2)}(\tau)$ and (b) $V_{\text{TPI}}(\tau)$ near $\tau = 0$ for different frequency separations (time-bin size 100 ps). All data are taken at $S = 0.01$ with a fixed laser-to-single-photon intensity ratio of $\eta = 0.2$.

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