

Second-order spectroscopy of a telecom band quantum dot single photon emitter

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Abstract: We directly retrieve the coherence properties of a quantum dot including fine-structure splitting (FSS) of a telecom-band quantum dot from a single Hong–Ou–Mandel (HOM) measurement. This method provides a straightforward measurement of fundamental properties of solid-state quantum emitters.

Fine-structure splitting (FSS) of semiconductor quantum dots (QDs) plays a crucial role in realizing high-fidelity entangled photon pairs (EPPs) [1], which are essential resources for quantum networks. However, accurately resolving small FSS values on the order of a few μeV remains challenging, as conventional first-order spectroscopy (e.g., $\mu\text{-PL}$ or Fabry–Pérot interferometry) is fundamentally limited by other broadening mechanisms such as thermal fluctuations and spectral diffusion, which obscure the underlying energy structure. Here, we demonstrate a second-order quantum spectroscopic approach based on Fourier analysis of Hong–Ou–Mandel (HOM) interference. By analyzing the temporal photon correlations, this method reveals the intrinsic phase evolution between fine-structure-split exciton states, achieving μeV -level resolution beyond the conventional spectral limit. It simultaneously measures other fundamental properties of the QD, such as decoherence time.

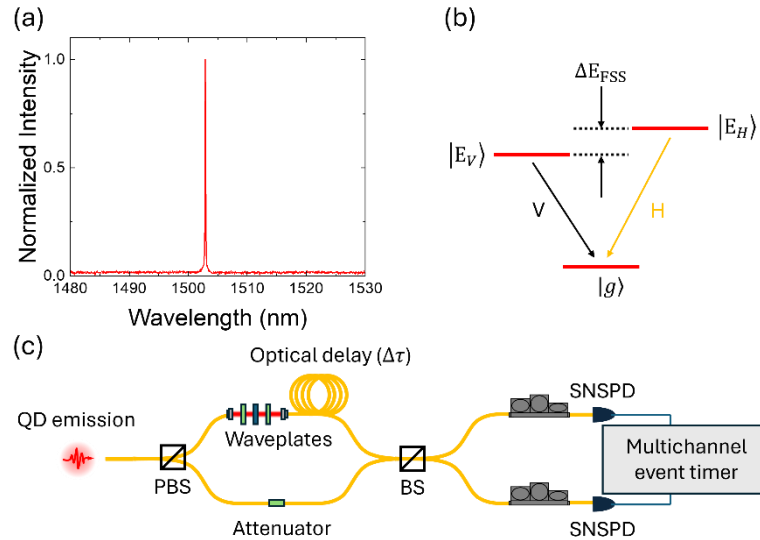


Figure 1. (a) Emission spectrum of a spectrally filtered telecom-band quantum dot (QD) centered at 1502.9 nm. (b) Energy-level diagram of the exciton state showing fine-structure splitting (ΔE_{FSS}) between orthogonally polarized transitions (H and V). (c) Schematic of the Hong–Ou–Mandel (HOM) interference setup used for second-order spectroscopic measurement. PBS : Polarizing beam splitter, BS : Non-polarizing beam splitter, SNSPD : Superconducting nanowire single photon detector.

We used a telecom-band InAs/InP QD embedded in a double solid immersion lens with a distributed Bragg reflector (DBR) [2] under quasi-resonant excitation. The exciton emission was spectrally filtered, Fig. 1(a). The exciton consists of two orthogonal fine-structure-split states, $|E_H\rangle$ and $|E_V\rangle$, separated by $\Delta E_{FSS} = E_H - E_V$, Fig. 1(b). The spectrally mixed exciton emission was directed to a polarizing beam splitter (PBS), where each output path contained a

superposition of the two fine-structure-split polarization components. In each arm, the polarization was subsequently adjusted using waveplates to ensure identical polarization alignment at the non-polarizing beam splitter (BS). One arm was delayed by one repetition period of the pulsed excitation laser, and the two paths were recombined at the BS to observe HOM interference, Fig. 1(c).

The input wavefunctions at the BS are given by

$$\begin{aligned}\psi_1 &= \sqrt{1-B}|E_H\rangle + e^{-i\Delta E_{FSS}t/\hbar}\sqrt{B}|E_V\rangle \\ \psi_2 &= \sqrt{B}|E_H\rangle + e^{-i\Delta E_{FSS}t/\hbar}\sqrt{1-B}|E_V\rangle,\end{aligned}$$

where B determines the relative population of the two energy states. The HOM interference as a function of delay time (Δt) can be modeled as [3]

$$G^{(2)}(\Delta t) = A * \left[e^{(-|\Delta t|/\tau)} - e^{(-\gamma|\Delta t|)} [(1-B) + B\cos(\Delta E_{FSS}\Delta t/\hbar)] \right] + G_0,$$

where A is the normalized amplitude, G_0 is an offset, and τ is the measure radiative lifetime (1.53(1) ns). The total decoherence rate $\gamma = 1/\tau + 2\Gamma^*$ includes the pure dephasing rate (Γ^*).

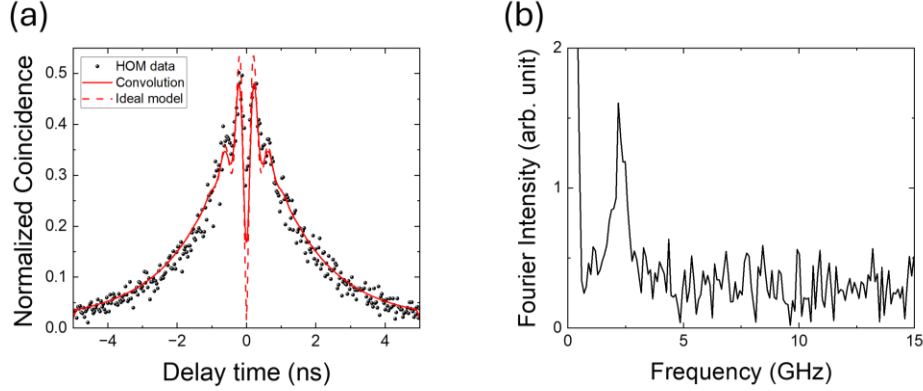


Figure 2. (a) Experimental Hong-Ou-Mandel (HOM) correlation (black dots) and model fits. Dashed and solid lines indicate the ideal case and the convolution with the system response (detector jitter) function, respectively. (b) Fourier-transformed spectrum of the HOM data, exhibiting a strong frequency component associated with the excitonic fine-structure splitting (FSS).

The Fourier transform of the measured HOM interference [Fig. 2(b)] reveals a distinct spectral peak at approximately 2.26 GHz, corresponding to an FSS energy splitting of 9.35 μ eV. Using this FSS value, the best-fit model yields the parameters $A=0.498(9)$, $B=0.77(4)$, $G_0=0.041(1)$, and $\gamma=4.3(4)$ GHz, corresponding to a pure dephasing time ($1/\Gamma^*$) of 550(40) ps (number in parentheses is uncertainty of one standard deviation of the fit). The model fit closely reproduces the measured HOM curve, Fig. 2(a). The slightly elevated $G^{(2)}(0)$ in the experimental data is attributed to minor polarization mismatch, incoherent components such as the phonon sideband, and the non-ideal transmission/reflection ratio (45:55) of the BS.

These results demonstrate that the FSS of a telecom-band quantum dot can be quantitatively extracted from the temporal beating observed in the HOM interference. This second-order spectroscopic approach achieves μ eV-level spectral resolution without relying on narrowband filtering or interferometric stabilization, providing a direct time-domain pathway to resolve intrinsic energy-level separations in quantum emitters. The demonstrated technique offers a robust and scalable route for characterizing fine energy structures in solid-state single-photon sources, extending beyond the limits of conventional first-order spectroscopy.

References

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