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Single photons – Photonics qubits: Generation, detection, and characterization

Experimental lab session: 8 hours Data analysis and report: 4 hours

Quantum Optics Laboratory

Introduction:

In photonic quantum information technology, quantum bits (qubits) are often encoded into single photons, typically utilizing their polarization or spin properties. These inherent properties of single photons offer a stable and easily manipulatable platform for encoding and processing quantum information:

1. Polarization-Based Qubits:

- **Horizontal (|H⟩) and Vertical (|V⟩) Polarization:** In a straightforward polarization-based qubit scheme, single photons are represented by horizontal (|H⟩) and vertical (|V⟩) polarization states, corresponding to the |0⟩ and |1⟩ quantum states, respectively. These states can be manipulated using basic optical components such as wave plates and polarizing beam splitters.
- **Superposition States:** By applying wave plates at specific angles, it is possible to create superposition states, such as |H⟩ + |V⟩ and |H⟩ - |V⟩, representing quantum states in a superposition of |0⟩ and |1⟩.
- **Quantum Gates:** Polarization-based qubits can be manipulated using polarizing beam splitters, wave plates, and other optical elements to perform quantum gates, facilitating quantum computation.

2. Spin-Based Qubits:

- **Circular Polarization:** Spin-based qubits are often implemented using circular polarization states, namely right circular polarization (|R⟩) and left circular polarization (|L⟩). These states correspond to the |0⟩ and |1⟩ quantum states, respectively.
- **Superposition States:** Superposition states, such as |R⟩ + |L⟩ and |R⟩ - |L⟩, can be generated using quarter-wave plates.
- **Quantum Gates:** Spin-based qubits can also be manipulated using wave plates and other optical components to perform quantum gates.

Advantages of Photonic Qubits:

- **Low Interaction with the Environment:** Photons interact weakly with their surroundings, making them less susceptible to decoherence due to environmental factors.
- **High Coherence:** Photons are naturally coherent and maintain their quantum states over long distances, which is advantageous for quantum communication.
- **Minimal Error Rates:** When handled properly, photons can exhibit low error rates, making them suitable for implementing reliable quantum operations.
- **Efficient Detection:** Single-photon detectors are available with high efficiency and low noise, enabling precise measurements.
- **Potential for Quantum Communication:** Photonic qubits are well-suited for quantum key distribution (QKD) and other quantum communication protocols due to their low-noise characteristics and the ability to transmit over long distances in optical fibers.

Photonic qubits have been at the forefront of many quantum technologies, including quantum cryptography, quantum computing, and quantum teleportation experiments. Therefore, developing efficient deterministic single-photon sources generating highly indistinguishable pure single-photons is essential for future quantum information processing.

Lab session: Generation, detection, and characterization of single photons from individual quantum emitters

General Session Objectives:

The primary goal of this session is to introduce students to the principles and techniques involved in generating, detecting, and characterizing single photons using single quantum dots (QDs) for applications in quantum information technology. The session will focus on assessing three key figures of merit for single photon sources: efficiency, purity (as characterized by Hanbury Brown-Twiss measurements), and indistinguishability (as characterized by Hong-Ou-Mandel interference measurements).

Learning objectives:

By the end of the session, the student will be able to:

- **Define single-photon source** and its role in photonic quantum information technology.
- **Explain quantum dots**, their behavior, and optical properties.
- **Design and carry out optical spectroscopy on generating and characterizing single photons from individual quantum dots.** In this session, by exploiting the closed-cycle optical cryostat combined with a confocal microscopy setup, CW, and pulsed femtosecond lasers, and superconducting nanowire single-photon detectors, the students design and carry out cryogenic micro-photoluminescence (uPL) spectroscopy, optical imaging and lifetime measurements of individual quantum emitters.
- **Perform advanced quantum optical characterizations of the generated single photons in terms of purity and indistinguishability** by designing and carrying out Hanbury Brown-Twiss (HBT) and Hong-Ou-Mandel (HOM) interference experiments, respectively.
- **Analyze experimental data to calculate the efficiency, purity, and indistinguishability** of single photon sources.

Sample and Equipment:

- Single quantum dot sample: InAs quantum dots embedded in GaAs
- Closed-cycle optical cryostat to cool down the sample (4 K)
- Excitation source: LEDs, CW tunable laser (780-805 nm), tunable pulsed femtosecond laser (680 – 1080 nm, 150 fs, 80 MHz)
- sCMOS camera, spectrometer
- Optical setups and components: Confocal microscope integrated into optical cryostat, polarizers, lenses, optical filters, single-mode fibers
- Single-photon detectors: Single-photon avalanche photodiodes and superconducting nanowire single-photon detectors
- Time tagger: time-correlated single photon counting module
- Hanbury Brown-Twiss setup for the second-order correlation measurement
- Hong-Ou-Mandel setup
- Laser safety goggles

Lab Session Outline:

1. **Introduction and Discussion:**

- Classic bits vs. Quantum bits, relevant quantum phenomena, e.g., superposition, entanglement.
- How do we encode classic bits and quantum bits? Photonics qubits and what are the main platforms.
- Photonic qubits - single-photon sources and their significance in photonic quantum information technology.
- Discuss the three main figures of merit of single photon sources and their characterization and corresponding experiments.
- A brief overview of the lab experiments and plan.

2. Safety briefing

- Discuss laser safety and the importance of handling equipment properly.
- Explain what happens if one ignores the safety regulations.

3. Setup and Alignment:

- Demonstrate the setup of the closed-cycle optical cryostat and confocal microscopy (Fig. 1).
- Align the optical components and lasers for efficient spectroscopy and imaging.

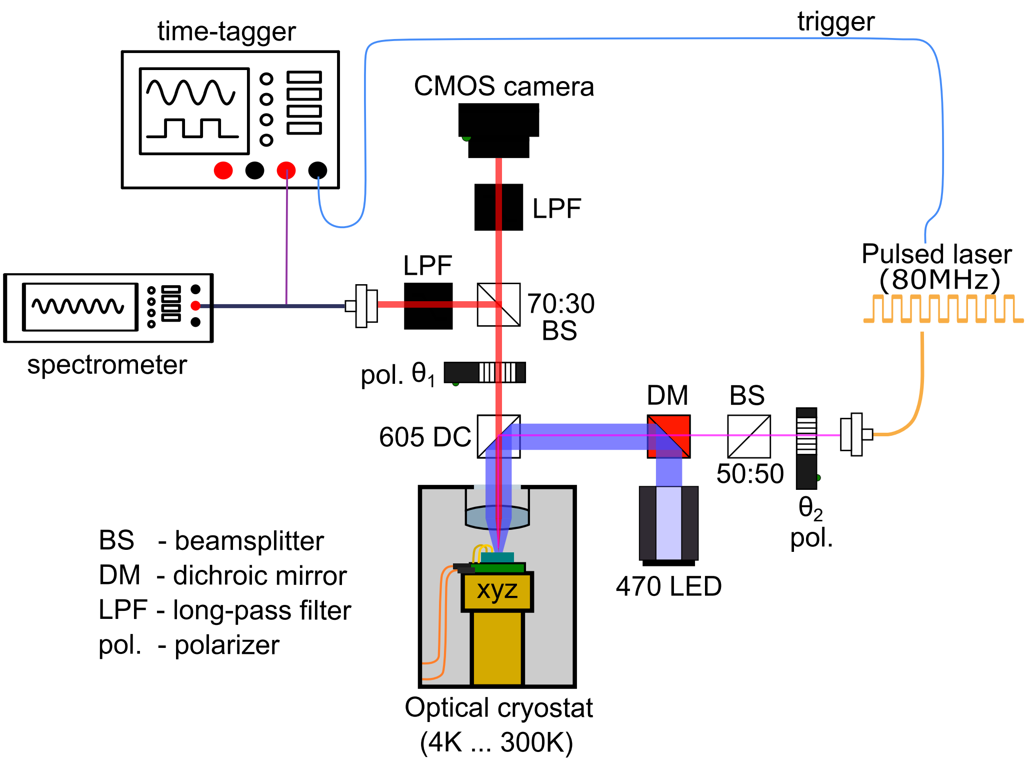

Fig. 1. The schematic of the optical cryostat combined with confocal microscopy setup for optical spectroscopy of individual quantum emitters in cryogenic temperature.

4. Optical Spectroscopy and imaging:

- Design and conduct cryogenic micro-photoluminescence (uPL) spectroscopy experiments.
- Use CW and pulsed lasers to excite and characterize individual quantum dots.
- Obtain the photoluminescence image of the quantum dot sample (if needed).
- Acquire photoluminescence spectra from individual quantum dots and correlate them in the photoluminescence image.
- Analyze the optical properties of emitted photons from several individual quantum dots: emission wavelength and linewidth by performing fitting a Gaussian and Lorentzian function.

5. Lifetime Measurements:

- Perform lifetime measurements of individual quantum emitters under pulsed femtosecond excitation using superconducting nanowire single-photon detectors and time-correlated single-photon counting modules.
- Discuss the significance of lifetime measurements in assessing quantum dot performance.
- Determine the radiative lifetime by implementing a fitting with exponential functions.
- Calculate the lifetime-limited (Fourier-limited) spectral linewidth
- Discuss the correlation of the extracted Fourier-limited linewidth with the experimentally obtained linewidth of the emission spectrum of each quantum dot.

6. Purity (Hanbury Brown-Twiss Measurements):

- Set up the Hanbury Brown-Twiss (HBT) interferometer (Fig. 2a,b).
- Design and conduct HBT experiments to assess photon purity (anti-bunching) (Fig. 2c).
- Analyze the obtained $g^2(0)$ values and discuss the purity of the quantum dot.

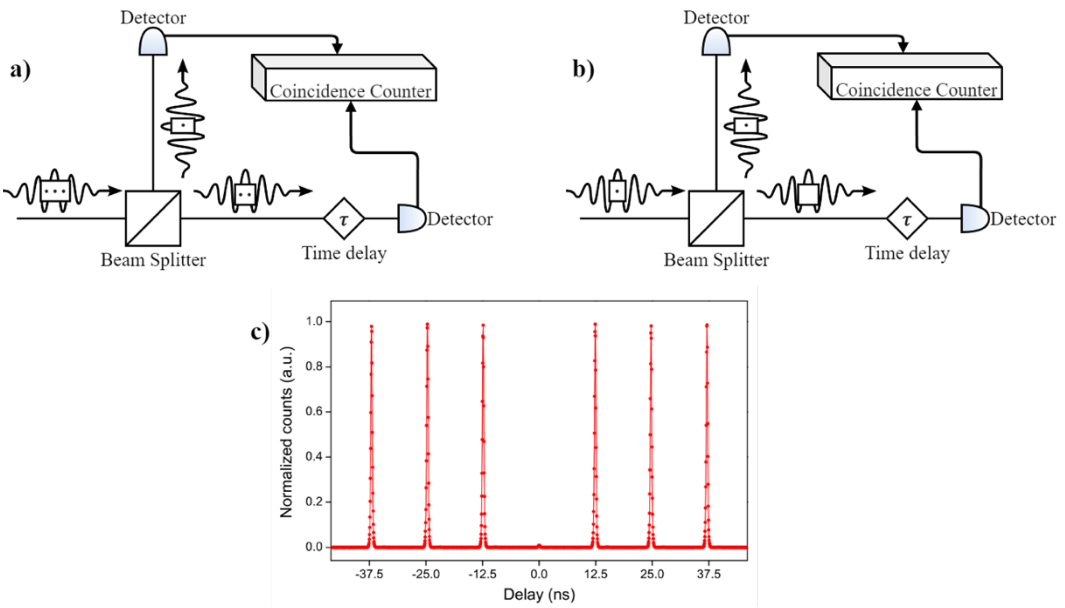

Fig. 2. A schematic of a typical HBT experiment for input values containing (a) multi-photons and (b) single-photons. (c) An exemplary second-order autocorrelation function ($g^{(2)}(t)$), obtained from a single-photon source.

7. Indistinguishability (Hong-Ou-Mandel Interferometry):

- Set up and calibrate the Hong-Ou-Mandel (HOM) interferometer (Fig. 3).
- Design and conduct HOM interference experiments to assess photon indistinguishability (Fig. 3).
- Analyze the observed interference patterns and coincidence counts and determine the indistinguishability of the quantum dot.

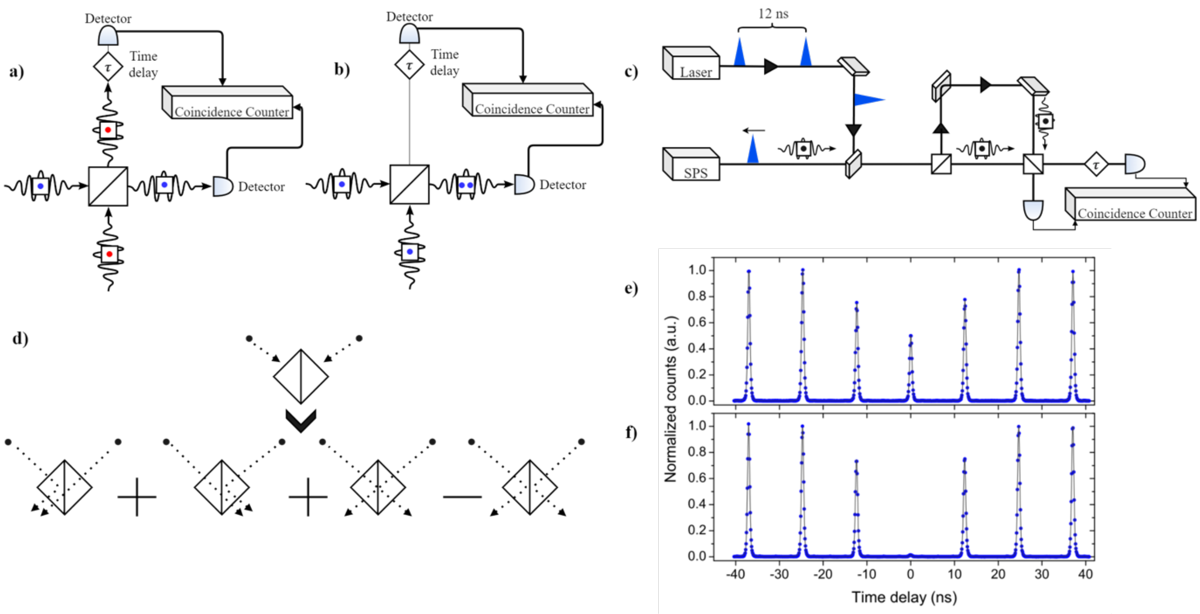

Fig. 3. A schematic representation of a HOM experiment for (a) distinguishable photons and (b) indistinguishable photons. (c) A schematic of a typical HOM setup. (d) Possible outputs and HOM effect. Exemplary second-order autocorrelation functions ($g^{(2)}(t)$) for (e) orthogonal and (f) parallel polarization obtained from a single-photon source.

8. Data Analysis and Calculation:

- Analyze experimental data to calculate efficiency, purity (using $g^2(0)$), and indistinguishability.
- Discuss the significance of these three figures of merit in evaluating single-photon sources.

9. Discussion and Conclusion:

- Review the lab results and observations in the context of the specified learning objectives.
- Discuss the practical applications of single-photon sources in quantum information science.
- Encourage further exploration of quantum technologies and research opportunities.

10. Q&A and Feedback:

- Invite students to get feedback on the lab session and wrap up the session.