Quantum Optics and Quantum Information Laboratory (OPT 253, OPT 453, PHY 434)

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Abstract: Quantum optics teaching laboratory consists of four experiments: (1) entanglement and Bell’s inequalities, (2) single-photon interference, (3) confocal microscope imaging of single-emitter fluorescence, (4) Hanbury Brown and Twiss setup. Fluorescence antibunching.

This 4-credit-hour-course introduces both undergraduate and graduate students to the basic concepts and tools of quantum optics and quantum information using modern photon counting instrumentation. Students will obtain both single and entangled photons and will carry out the experiments confirming their nonclassical behavior. The classes will be held twice per week, total six hours per week.

Lab 1. Entanglement and Bell’s inequality violation

Entanglement is the most exciting and mysterious property of some quantum mechanical systems when property of one particle depends on the property of the other. It does not matter how far apart such particles are located. Among the best known applications of entanglement are quantum communication and quantum state teleportation. Bell’s inequality is a classical equation.

For classical case some relation \( S \leq 2 \). For nonclassical particles it is violated.

The schematics of teaching experiment to produce polarization-entangled photons and Bell’s inequalities’ violation measurements is shown in the Figure 1, left. In this experiment spontaneous parametric down conversion process in two type-I BBO crystals produces two photons with \( 2\lambda_{inc} \). Light from a 100 mW, \( \lambda_{inc} = 363.8 \) nm cw ion argon laser passes through a blue filter and then a quartz plate. A mirror redirects the beam through a pair of BBO crystals that are mounted back-to-back with one rotated 90° from the other about the beam propagation direction. Down-converted photons exit the crystals in the direction of a cone (Figure 1, center). They are detected by a pair of single-photon counting avalanche photodiode modules (APDs) mounted on diametrically opposite points of the down-converted cone. In this arrangement each crystal can support downconversion of one pump polarization.

A 45° polarized pump photon can downconvert in either crystal, producing a polarization entangled pair of photons. Quartz plate rotation compensates phase \( \Delta \) introduced by the crystals.

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|H\rangle + |V\rangle \rightarrow |V, V\rangle + \exp(i\Delta)|H, H\rangle
\]

Coincidences are detected by a fast logic circuit (counter) card inside a PC. Figure 1, right shows ~\( \cos^2(\alpha - \beta) \) coincidence count dependence on a relative angle \( \alpha - \beta \) between two linear polarizers A and B located in front of each APD. In this experiment an angle \( \beta \) of a linear polarizer B varies at two different fixed angles \( \alpha \) of a polarizer A.

2007-year students showed a violation of Bell’s inequality in the Clauser-Horn-Shimony-Holt form (\( S \geq 2.65 \)).
**Lab 2. Single photon interference (Young’s double slit experiment and Mach-Zehnder interferometer)**

Young’s double slit experiment shows wave-particle duality (Figure 2, left). Measurements were made using He-Ne laser beam, attenuated to a single photon level, and electron multiplied (EM), cooled CCD camera iXon of Andor Technologies. Mach-Zehnder interferometer (Figure 2, right) is used for the demonstration of a single-photon interference after removing “which-way” information (identification of the path).

**Lab 3 and Lab 4. Single photon source**

Single photon source (SPS) is a key hardware element in quantum cryptography. In difference with single photons produced by attenuation of a laser beam, SPS has much higher intensity. In addition, it is not contaminated by pairs and triples of photons. All photons in the SPS are separated from each other (antibunching). To produce single photons a laser beam is focused onto a single emitter which emits only single photon at a time. In Lab3 single or antibunched photons will be obtained, and in Lab 4 photon statistics will be measured to proof photon antibunching.

**Lab 3. Confocal microscope imaging of single-emitter fluorescence**

Several ps pulse duration, 76 MHz pulse repetition rate excitation at 532-nm is used for confocal microscope single-emitter fluorescence imaging (Figure 3). DiI dye and CdSe colloidal quantum dots are used as emitters.

**Lab 4. Hanbury Brown and Twiss setup. Fluorescence antibunching**

Figure 4, left shows Hanbury Brown and Twiss setup for fluorescence antibunching measurements. A typical confocal fluorescence microscope image of a single CdSe quantum dot is shown in Figure 4, right as well as histogram of coincidence counts of this quantum dot fluorescence showing fluorescence antibunching (dip at zero interphoton time) under pulsed, 532-nm irradiation. TimeHarp 200 PC card is used for a start-stop measurements.