

# **Quantum optical methods in metrology**

Thesis

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## **Premise of the work**

Quantum mechanical entanglement, study of entangled states has been in focus of many recent scientific researches. One of the most common ways to produce such entangled states is the generation of correlated photon pairs. Experiments with entangled photon pairs have opened a whole field of experimental quantum optics and quantum metrology research.

Experiments with entangled photon pairs have opened a whole field of experimental quantum optics and quantum metrology research. The most convenient source for generating such entangled photon pairs is a nonlinear optical process of spontaneous parametric down conversion (SPDC). In the process of SPDC, a photon of pump-laser radiation decays inside a non-linear optical crystals into two photons, often called “twins” because they are perfectly correlated in all physical parameters of their state (direction, energy, polarization, etc.). For a long time the SPDC process has been considered as a convenient source of single-photon states. This technique does have an advantage over other methods, because the photons are created in pairs as twins. The detection of one of them indicates, with certainty, the existence of the other one with particular physical properties. Because of the energy and momentum conservation requirements, the direction and energy of the detected photon can be used to predict not only the existence, but also the direction and energy of the other photon in the pair.

## **Purpose of the work**

The purpose of my work was to establish an experimental setup for the generation of correlated photon pairs, the use of these photon pairs in quantum optical metrology and the study of statistical properties of new phenomena, such as surface plasmon oscillation. I have built an experimental setup based on the pumping of a UV laser for the generation of correlate photon pairs. With this setup I have developed new measurement processes exploiting the advantageous properties of the photon pairs.

I have measured the quantum efficiencies of photodiodes (two detector process) and photomultipliers (single detector process) without the use of a standard etalon.

I have developed a special light source with pre-determined number of photons. This light source is controllable at the photon level and enables us to produce a pre-determined number (even only one) of photons in a certain time window. A photon source like this could be useful in many different optical measurement applications such as quantum cryptography and quantum information processing including designing new optical quantum logic gates. I also developed a process and an electronic unit for the measurement of photon statistical properties.

Taking advantage of my experiments with correlated photon pairs and their photon statistics I measured the statistical properties (time interval statistics, photon number distribution, correlation function) of the light generated by surface plasmon oscillations and compared them to those of the exciting laser.

## **Methods**

During my work I have generated correlated photon pairs by the non-linear process of spontaneous parametric down conversion. For the conversion I pumped a KDP crystal with the 351.1 nm line of a UV laser. During the process of SPDC, a photon of pump-laser radiation decays inside the non-linear crystals into two photons with lower frequencies. The photon pairs generated by SPDC are highly correlated. To produce such photon pairs with this process the phase synchronization inside the crystal has to be assured.

I used chilled avalanche photo diodes in the photon counting regime and photomultipliers for the detection of the photon pairs and for the quantum efficiency measurements. To show that the photon pairs are produced coincidentally I developed a so called “start-stop” signal processing electronic unit. Capitalizing the coincidence of the photon pairs and utilizing the signal processing electronic unit I proposed a new method for the estimation of refractive index of fluids.

The basic concept for the measurement of quantum efficiency is that the photon pairs arrive at the surface of the detectors simultaneously. If one of the detectors fails to

count, that must be the default of the detector. Developing the light source with the predetermined number of photons I exploited the property of photon pairs, that the detection of one of the pair (signal) gives us information of the other (idler). Therefore with the proper opto-electronic devices we can control the output of the idler beam.

I used the devices, signal processing units and methods developed to study the properties of correlated photon pairs to study the statistical properties of the light generated by surface plasmon oscillation and recombination. With photon counting detectors and a proper software time interval statistics, photon-number distribution and correlation function of the generated light were determined and compared to those of the exciting laser.

## **Thesis**

1. I have developed an experimental setup for the generation of correlated photon pairs and measured their coincidence properties. Based on the coincidence peaks the number of correlated photon pairs in the generated light is 3 magnitudes larger than the number of photons in the background. I have determined the angular distribution of the generated photon pairs and their photon statistical properties with a time resolution of 30 psec. I proposed a new method for the measurement of refractive index of fluids based on correlated photon pairs. [1,6,7]

2. I have developed a new two-detector technique for the measurement of quantum efficiency without the use of a light etalon based on correlated photon pairs. With this new method I have determined the quantum efficiency of avalanche photo diodes and single photon counting modules. [1]

3. I have developed a new one-detector technique for the measurement of quantum efficiency of photomultipliers. I have measured the distribution of amplitudes for the single- and double-photon counts. Based on this new method I determined the quantum efficiency of the tested photomultipliers. [1]

4. I have proposed and developed a light source with the pre determined number of photons. With this light source the generation of a given number of  $n$  photons ( $n = 1, 2, 3, 4, 5, \dots$ ) in a time interval is achievable. I have developed the opto-electronic units necessary to control this new device. I have demonstrated the work of the light source in cases of different set photon numbers. I have shown that the developed light source can be useful for different applications, such as calibration of sensitive photo detectors or the study of photon statistical measurements. [2,3]

5. I have shown, that the statistical properties of the light emitted by the recombination of surface plasmon oscillations generated by laser light are identical to those of the exciting laser at low intensities ( 5mW, He-Ne laser). The statistical properties have been determined by the parameters of photon-number distribution and correlation function. [4,5]

### **Publications related to my PhD work:**

- [1] D. Oszetzky, *Application of correlated photon pairs in optical metrology*, Quantum Electronics APH B **20**, 185 (2004).
- [2] D. Oszetzky, A. Czitrovszky, A. V. Sergienko, *Designing a special light source with a pre-determined number of photons*, SPIE **5161**, 352 (2003).
- [3] D. Oszetzky, A. Nagy, A. Czitrovszky, *Controllable photon source*, SPIE **6372**, 39 (2006).
- [4] N. Kroó, A. Nagy, A. Czitrovszky, D. Oszetzky, H. Walther, *Surface plasmons and photon statistics*, Journal of Modern Optics **53**, 2309 (2006).
- [5] N. Kroó, S. Varró, Gy. Farkas, D. Oszetzky, Nagy, A. Czitrovszky, *Quantum Metal Optics*, Journal of Modern Optics **54**, 2679 (2007).

- [6] D. Oszetzky, A. Czitrovszky, A. Nagy, *Photon statistic measurement of down-converted light*, SPIE **6028**, 449 (2005).
- [7] D. Oszetzky, P.Gál, A. Czitrovszky, *New method for estimation of the refractive index of aerosols using entangled photon pairs*, Journal of Aerosol Science **33**, 281-282 (2004).