Ultrafast Quantum Optics with Spectral Resolution

Abstract

Optical photons are exceptional, reliable carriers of information and yet also excellent, extremely sensitive probes of matter. The spectro-temporal degree of freedom (DoF) of a photon plays an important role in these properties. In the context of emerging quantum technologies and partially that of fundamental phenomena, this thesis explores the spectral DoF of single-photon and single-photon level broadband light.

The thesis is based on a series of publications concerned with a relatively wide range of problems in quantum and ultrafast optics. Photon-starved light in a temporal mode of an ultrashort pulse (spectrally broadband) is the "common denominator" of these works. So is a unique measurement device developed and applied for the studies – a very fast single-photon-sensitive camera. Its creation and characterization enabled or greatly simplified many of the presented experiments. As a fairly universal scientific tool, it still holds great potential for further applications.

The predominantly experimental work presented herein encompasses 5 studies. In the first one, we characterize hybrid entanglement between the transverse and spectral DoF for pairs of photons generated in a non-collinear type-I spontaneous parametric down-conversion process. The second study explores the two-photon interference with spectrally-resolved single-photon detection, as a method to dispersively probe light-matter interactions. In the third experiment, we turn from single photons to weak coherent states (single-photon level) and demonstrate a variation of the electro-optic shearing interferometry, albeit based on the second-order intensity correlation measurement and particularly suitable for ultrashort pulses in the near-infrared. The fourth study demonstrates an electro-optic single-photon-level-compatible ultrafast implementation of a coherent time-frequency transformation – Fractional Fourier Transform which is of interest itself as a generalization of the ordinary Fourier Transform and also constitutes an indispensable building block of the next experiment. In the final part, we turn to the frequency-domain quantum metrology and demonstrate a spectral super-resolution method motivated by the recent rapid developments in quantum-inspired far-field super-resolution imaging techniques. The presented method can be regarded as a frequency-domain implementation of the ideas of image-inversion interferometry. Compared with a spectral intensity measurement, it reduces the resources required to estimate a separation between two spectral features.