Abstract

In recent years, the spectro-temporal degree of freedom of quantum light has emerged as a promising platform for high-dimensional quantum information processing. Compared to already well-known polarization and spatial degrees of freedom, it offers high-dimensional encoding bases while being compatible with the existing telecom fiber network, enabling efficient transfer of quantum information over long distances. However, utilizing the spectro-temporal degree of freedom requires control of the temporal envelope and spectrum of optical pulses. These operations need to be compatible with quantum requirements, such as lack of amplification and low loss.

The subject of this thesis is experimental realization of the spectro-temporal control of quantum light pulses by employing electro-optic phase modulation. I created a new electro-optic experimental platform to shape temporal envelope and spectrum of single-photon pulses. The key component of such manipulations is a time lens, which is provided by the optical space-time duality relating spectro-temporal optics to already well-studied spatial optics. Within the thesis I developed two different types of time lenses, which I employed to modulate spectra of single-photon pulses. In particular, I used photonically generated and very wideband radio-frequency (RF) signals, creating aperiodic and Fresnel time lenses, which lift the technical limitations of time lenses shown to-date and enable new important applications.

First, I investigated an aperiodic time lens, which utilized a photonically-generated RF signal. In particular, the required RF signal was generated from the optical pulse train, which enabled perfect synchronization of the modulated and modulating signals, overcoming the challenges of the standard approach. I showed an 18-fold bandwidth compression of heralded single-photon spectra, enhancing their maximal intensity by a factor of 5, including non-unit system transmission. By employing classical light, I also performed an in-depth analysis of such a time lens, including the broadened coherence time and its wide range central wavelength tunability. Finally, I tested a unique feature of such a time lens: its aperiodicity, i.e. the ability to act on non-repetitive signals enabled thanks to the photonic RF signal generation.

Then, I used a set of such time lenses to modulate the joint spectra of entangled photon pairs. I achieved two-photon spectral bandwidth compression, with the ability to fine-tune the central wavelength of the output photons. In particular, I tested the spectral compression of entangled photons and the manipulation of photon-pair spectro-temporal correlations. I used the same setup to measure the joint temporal intensity of the two-photon spectro-temporally entangled state, drastically reducing the system complexity compared to the previously approaches based on nonlinear temporal gating.

The main outcome of the thesis is the development of a Fresnel time lens, which incorporated wideband, complex RF signals. It enabled reaching the output spectral bandwidth of tens or hundreds of MHz. I tested the generation of the arbitrary RF signals driving the electro-optic modulator in the context of spectral bandwidth conversion. I employed this approach to single-photon pulses, achieving compression of over two orders of magnitude while increasing maximal spectral intensity by a factor of 60. Such a Fresnel time lens creates a missing connection between GHz and MHz regimes of single-photon bandwidths, enabling the creation of hybrid quantum networks that employ both ultrafast optics and matter-based quantum devices such as quantum memories or quantum gates.