Shaping Entangled Photon Pairs

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Abstract. We demonstrate automated amplitude and phase modulation of entangled photon pairs with attosecond precision, different autocorrelation measurements, and the observation of nonlocal effects, such as an increase of the coherence time due to spectral filtering.

Introduction

Nonlocal effects in quantum mechanics have been investigated ever since Einstein, Podolsky, Rosen, and Bohr have started the discussion. Entangled photon pairs produced by spontaneous parametric down-conversion (SPDC) have become one of the main workhorses to observe nonlocal effects, and nonlocal correlations were investigated with respect to polarization, energy, or wave vector. In SPDC a pump laser photon of frequency ω_p and wave vector $\boldsymbol{k}_p$ produces a pair of correlated photons (signal and idler) which have frequencies ω_s and ω_i and wave vectors $\boldsymbol{k}_s$ and $\boldsymbol{k}_i$. The three photons must obey energy conservation and conservation of wave vector (phase matching). While the pair as a whole must have well defined properties, the individual photons have largely undetermined properties. In the meantime, many experiments have shown clear evidence of nonlocal effects such as violating Bell's inequalities. If time-energy entanglement is used, nonlocal effects have for example been demonstrated through the appearance of fourth-order interferences among distant interferometers. Recently, the Silberberg group has demonstrated in a beautiful set of experiments that techniques very similar to those used in femtosecond pulse shaping can be employed to manipulate the wave function of a time-energy entangled photon pair [1]. Based on these experiments, we demonstrate simultaneous phase- and amplitude shaping of entangled photon pairs with an attosecond precision. This allows for a pulse shaper-assisted realization of unbalanced interferometers and the shaper-assisted detection of nonlocal modulations of the two-photon wave function.

Experimental Methods

The down-converted entangled photon pairs are produced by focusing a 5 W continuous wave pump laser in a PPKTP crystal. The spectrally broadband light is send through a standard prism compressor consisting of 4 prisms, with the prism separation such that all material dispersion is compensated for. A spatial light modulator is positioned in the symmetry plane of the prism compressor. Time coincidences are detected by sum-frequency generation of the shaped down-converted light in a second PPKTP crystal and the sum-frequency photons are recorded by a single-photon counter. This experimental setup is similar to that reported by the Silberberg group [1]. The measured quantity, the second order coherence function, is simplified in the case of a delta-like pump to the form

$$G^{(2)}(t_s - t_i \approx 0) = \left| \int d\omega_s M_s(\omega_s) M_i(\omega_p - \omega_s) \xi(\omega_s) \right|^2 . \tag{1}$$

$M_j(\omega_j), j = s, i$ denote some transfer function experienced by the photons, and $\xi(\omega)$ is a function determined by the phase matching condition of the crystal.

Results and Discussion

First, we demonstrate coherent phase and amplitude modulation of time-energy entangled two-photon wave functions based on computer-controlled pulse shaping techniques [1, 2]. The combination of the two allows generating transfer functions which imitate most linear optical elements and more complex linear optical arrangements, such as interferometers. Typically, unbalanced interferometers are used to measure correlations and an example for a shaper-assisted (without any moving parts) autocorrelation of the two-photon wave function is shown in figure 1. The delay was scanned from -200 to +200 fs for both interferometric (left side) and intensity-like (right side) autocorrelation.

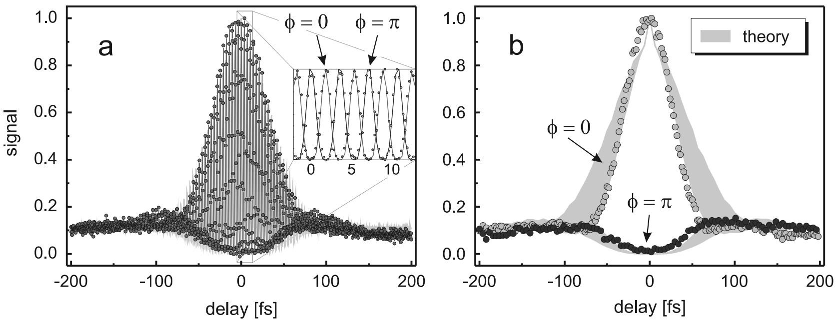

Fig. 1. Interferometric and intensity like autocorrelations of an entangled two-photon wave packet. Both- interferometer exit ports are measured.

By dynamically adjusting the transfer function the autocorrelation trace can be recorded with a minimum delay increment of 40 as, which is determined mostly by the spectral resolution of the setup. Contrary to the mechanical version of a Michelson interferometer the pulse shaper allows to delay the slowly varying envelope without changing the phase delay of the carrier wave. On the right side in figure 1 the result of such a measurement is presented. The rapid oscillations have disappeared and only an intensity-like autocorrelation trace remains. Moreover, the pulse shaper allows switching between the two exit ports of the interferometer by applying an additional phase shift of π to the delayed replica in the transfer function. The resulting curve is the complementary signal to the previous measurement in the sense, that the sum of their energies is equal to the amount of energy entering the interferometer. From the two intensity-like autocorrelation traces, we can directly derive the visibility of the two-photon wave function. All experiments agree well with the appropriate simulations (grey background).

Finally, we demonstrate the possibility to perform shaper-based quantum optical experiments. To that end two different transfer functions were applied to the signal and the idler part of the spectrum. Through spectral amplitude filtering in one beam path it is demonstrated that the other beam path is modified accordingly when the coincidences are detected. Recently, Bellini et. al performed similar experiments [3] based on filters and standard mechanical interferometers. Here, we replaced all optical elements by applying the corresponding transfer functions to the pulse shaping apparatus.

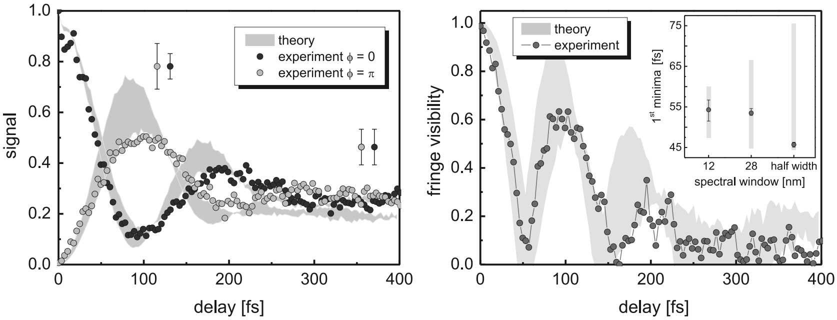

Fig. 2. Due to the entanglement the spectral narrowing of the idler photon influences the intensity-like autocorrelation of the signal photon and the extracted visibility function. The inset shows the position of the first minimum of the visibility as a function of the width of the spectral slit.

An example is shown in figure 2. Amplitude and phase modulation are required, first, to spectrally filter the idler side of the spectrum and, second, to realize a shaper-assisted interferometer on the signal part of the spectrum. For a fixed width of the spectral slit the shaper-based interferometer performs an intensity-like measurement of both exit ports of the simulated interferometer. The result of such a measurement is shown on the left side of figure 2. From these two traces the fringe visibility is constructed and the position of the first minimum is a reasonable measure for the coherence time of the wave function. The inset shows the position of the first minimum as a function of the width of the spectral slit, clearly demonstrating that the temporal coherence decreases as the width of the spectral slit increases.

Conclusions

We demonstrated that time-energy entangled photon pairs can be modulated in phase and amplitude similar to broadband laser pulses. The wave function was analyzed through autocorrelation methods and shaper-based quantum optics experiments were demonstrated.

Acknowledgements. This work was supported by NCCR Quantum Photonics (NCCR QP), research instrument of the Swiss National Science Foundation (SNSF).

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