Electro-optic Fourier Transform Chronometry of Pulsed Quantum Light

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Abstract—We demonstrate temporal envelope measurements of ultrashort optical pulses without time resolved detection. We apply our technique, which is the time-frequency conjugate measurement to Fourier-transform spectrometry, to experimentally measure the pulse envelope of classical and heralded single photon pulses.

Keywords—ultrafast photonics, spectral shift, single photon, Fourier transform, interferometry, electro-optic

I. INTRODUCTION

The temporal–spectral mode of photons is a promising platform for quantum information processing due to its potential for implementing high dimensional networks in fiber and chip based photonic devices. To realize such a platform, the temporal envelope pulse characterization of short optical pulses with single picosecond time resolution is required. In particular, here we introduce a technique for measuring the temporal energy envelope of the optical pulses based on tunable electro-optic spectral shearing interferometry. The proposed technique is based on the time-frequency Fourier analogue of Fourier transform spectrometry. It can be viewed as interchanging the roles of time and frequency in a Fourier transform spectrometer. Unlike the traditional intensity autocorrelations methods that rely on nonlinear techniques to measure ultrashort pulses, this method is a coherent and linear optical process that is applicable to quantum light [1].

Fig. 1. Conceptual schematic of the Fourier transform tunable electro-optic spectral shearing interferometry. BS: Beam Splitter, PD: Photodiode

II. TUNABLE ELECTRO-OPTIC SPECTRAL SHEARING INTERFEROMETRY

In this interferometric method as conceptually shown in Figure 1, the optical pulse is employed to measure itself. The optical pulses from a fs laser at 1560 nm propagate through a balanced polarization Mach-Zehnder interferometer (MZI) where a tunable spectral shear is applied in one arm of the interferometer. The frequency of the optical pulse is scanned with respect to its replica in the reference arm by applying a range of equally spaced spectral shears. The tunable spectral shear is applied using an electro-optic phase modulator (EOPM) driven by a RF signal generated using an amplified electronic pulse from a fast photodiode that is fed by a beam pickoff from the laser output [2]. A half-wave plate and a polarizing beam splitter are used before the fast photodiode to control the incident optical intensity. This in turn controls the amplitude of the RF driving signal for the EOPM and hence enables the tunability of the spectral shear. Then a photodiode at the interferometer output is
used to measure the integrated energy per pulse as a function of the spectral shear. This process is repeated until the spectrally sheared pulse is clear of its replica so that there is almost no overlap between the two arms of the interferometer in the spectral domain.

We first demonstrate our technique with classical laser pulses with 0.50 nm spectral bandwidth. Figure 2(a) shows the measured output intensity as a function of the spectral shear. The fringe visibility decreases with increasing spectral shift due to the reduction in spectral overlap. The spectral shift was performed only in one direction (blue shift) resulting in a fringe pattern for half of the optical pulse. We mirror this pattern to obtain the full symmetric fringe pattern (Figure 2(a)). The temporal energy envelope of the optical pulse is achieved by taking the AC component of Fourier transform of the interference fringes with results shown in the Figure 2(b). The calculated temporal width of the optical pulse is $7.48 \pm 0.02$ ps which is close to theoretical expectation ($7.61$ ps) for the optical pulse with 0.5 nm spectral bandwidth calculated based on second moment calculation.

To verify the validity of our measurement, the impact of adding dispersion to the pulse is investigated. Pulses of identical spectral bandwidth are sent through a variable length of PM fibre (dispersion) which leads to pulse broadening in the temporal domain without change in the spectral domain. The increase in temporal width corresponds to the amount of added dispersion as shown in Figure 2(c). The measured temporal widths after adding PM fibre in the setup are consistent with the theoretical model. We then demonstrate the capability of the method to measure the temporal duration of heralded single photon pulses generated through a spontaneous parametric downconversion process. One of the photons is spectrally filtered 0.5 nm bandwidth and then goes through the polarization-based MZI. The other photon is directed straight to a single photon detector to act as a herald. The Fourier transform of the resulting interference fringes was taken in order to calculate the temporal envelope of the single photon. We calculate a temporal width of $7.50 \pm 0.04$ ps for the single photon which is close to the measured temporal width of the classical optical pulse.

### III. Conclusion

The energy envelope of ultrashort classical and quantum light pulses was measured using Fourier-transform chronometry. It is a linear optical technique based on tunable electro-optic spectral shearing interferometry where the pulse temporal envelope is determined by measuring frequency dependent autocorrelation. The technique was validated by investigating the effect of bandwidth modification [3] and added dispersion on the measured pulse duration.

### Acknowledgment

The experimental part of this work was carried out within the First TEAM programme of the Foundation for Polish Science (project no. POIR.04.04.00-00-5E00/18), co-financed by the European Union under the European Regional Development Fund. A part of this work was supported by the National Science Centre of Poland (project no. 2019/32/Z/ST2/00018, QuantERA project QuICHE).

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