How two-photon interference captures the interaction of an ultra-fast photon and atomic vapor in the bandwidth-mismatched regime?

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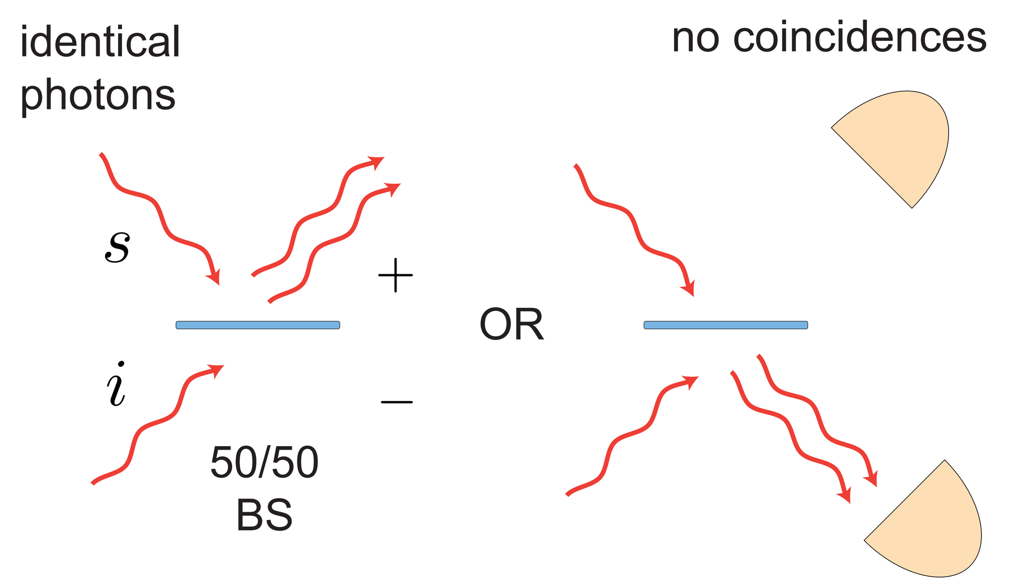
Single-photon holography

Two-photon interference combined with resolved coincidence detection recently enabled precise characterization of a single photon spatial wavefunction [1]. The method, reminescent of classical holography, employs interference of a signal (s) and reference (i) photons on a balanced beamsplitter (50/50 BS) followed by spatially-resolved detection of single-photon coincidences between s and i. Map of the coincidences in the position coordinates corresponding to the s and i photons is the analogue of a classical hologram and carries a footprint of the wavefront difference between s and i.

Fundamentally the method relies on the bosonic nature of photons which is reflected in the simplest scenario of two-photon interference with identical photons.

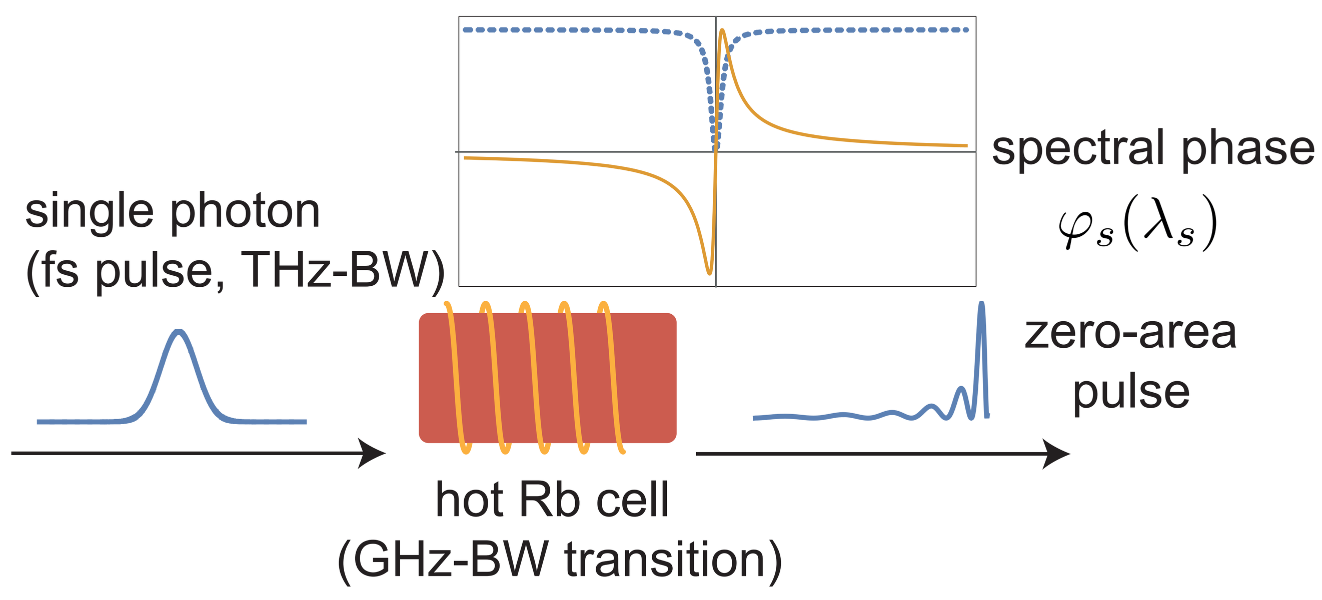


Zero-area pulses

Vastly studied in the classical regime the zero-area pulses arise from a bandwidth-mismatched resonant interaction of a broadband (ultrafast, THz-width) light pulse with a narrowband and dense medium (e.g. atomic vapor with GHz-width line). In the temporal domain the envelope of the zero-area pulse consists of a series of alternating +/- lobes.

Only recently a zero-area pulse has been characterized for a single photon with homodyne detection - a robust method yet inherently limited by the shot noise of the local oscillator (LO) and requring the state-of-the-art adaptive optimization of the LO mode [2].

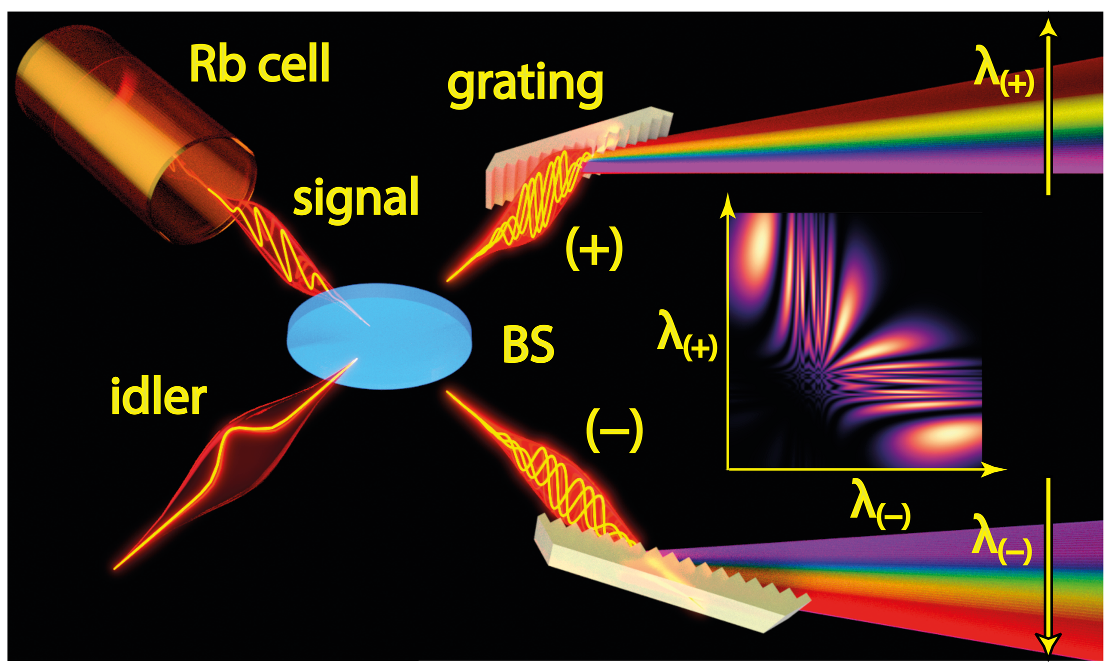
Interestingely formation of zero-area pulses is one of the few methods to interface broadband (e.g. solid-state) photons with narrowband (atomic) media without resorting to two-photon processes.



Spectral single-photon holography

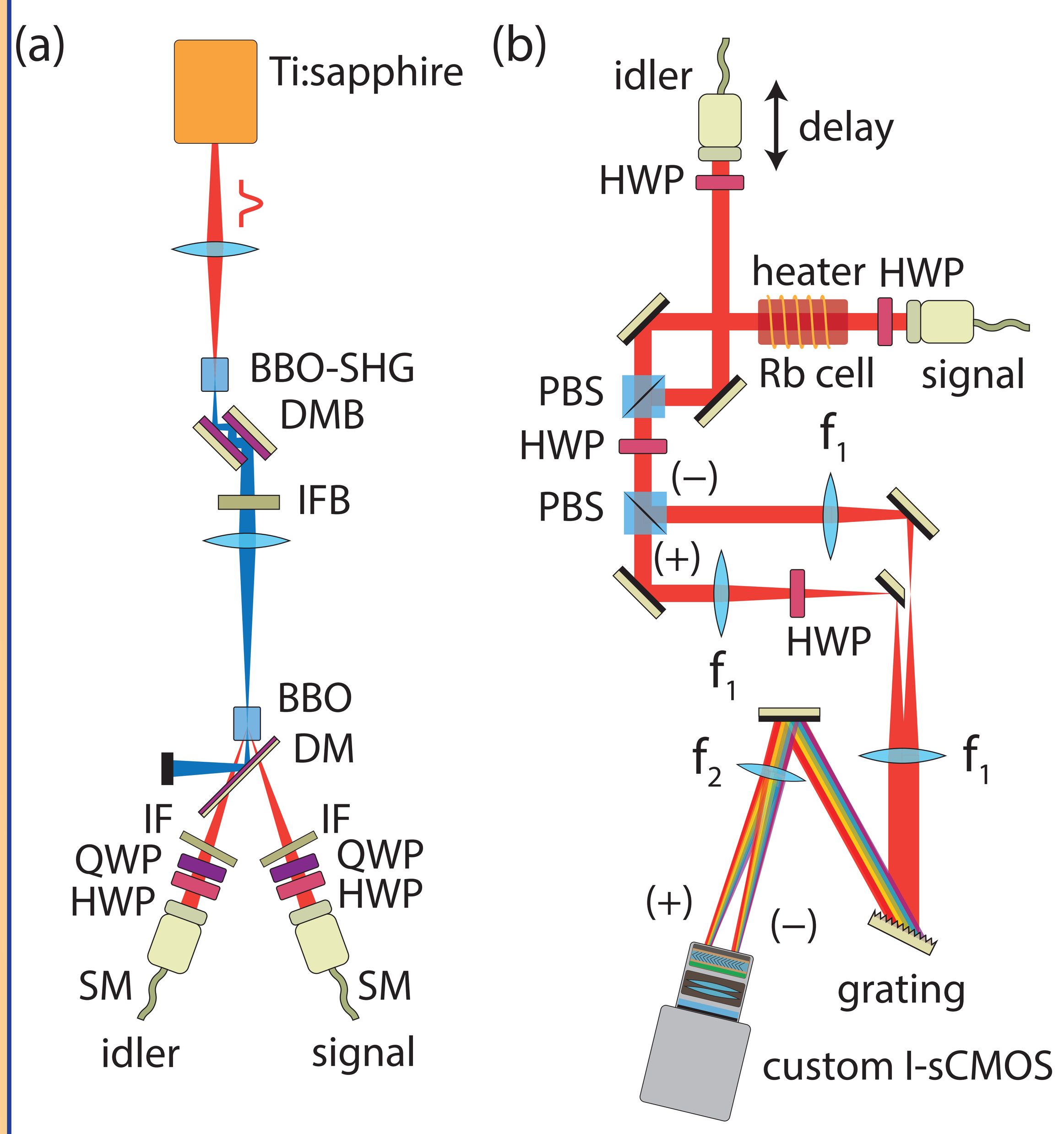
Combining single-photon holography with spectral resolution provides a tool for characterizing spectral phase profiles of single-photon zero-area pulses. Importantly, the bandwidth-mistmatched interaction forming the single-photon zero-area pulse is nearly purely dispersive, very rarerly leading to the absorbtion of the photon, yet imprinting a broad spectral phase profile.

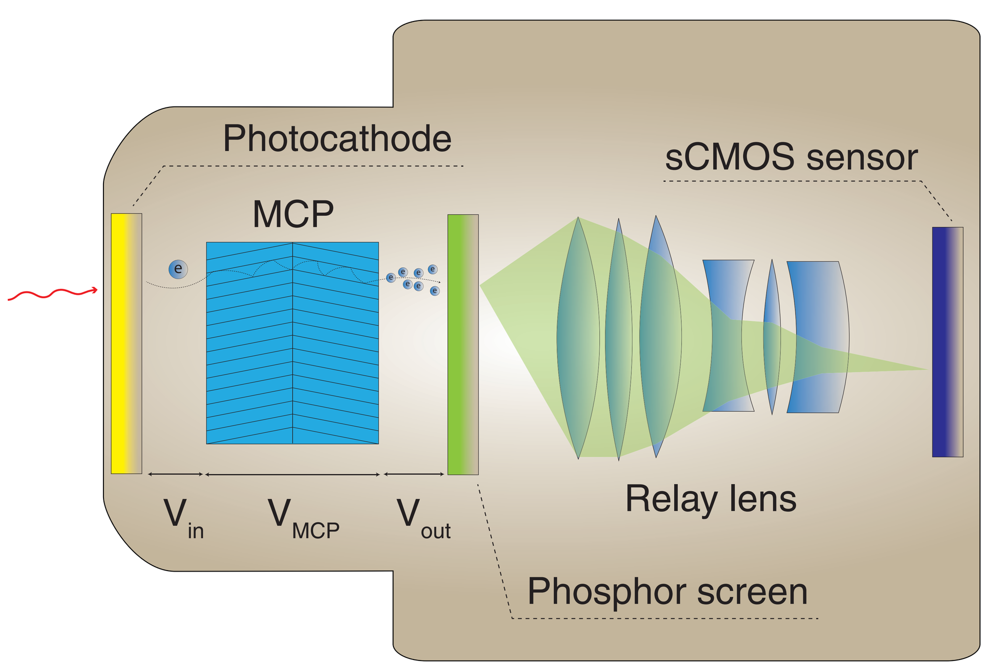
To reconstruct the spectral phase we start with a pair of indentical 100 fs photons (signal and idler). One of them passes through a hot Rb vapor cell obtaining the zero-area shape. Both meet at a balanced beamsplitter followed by diffraction gratings (+/-) faciliating spectral resolution. Histogram of coincidences detected for spectral coordinates of +/- ports contains the footprint of the spectral phase which can be recovered with standard Fourier-domain processing and 2D unwrapping.



Experiment

Experimental setup [3] consists of two-photon state generation (a) via SPDC pumped with a SHG of a 100 fs pulse from Ti:sapphire laser; and two-photon interferometer (b) with a heated Rb cell in one arm and a spectrally-resolved single-photon detection facilitated with a custom fast intensified camera.



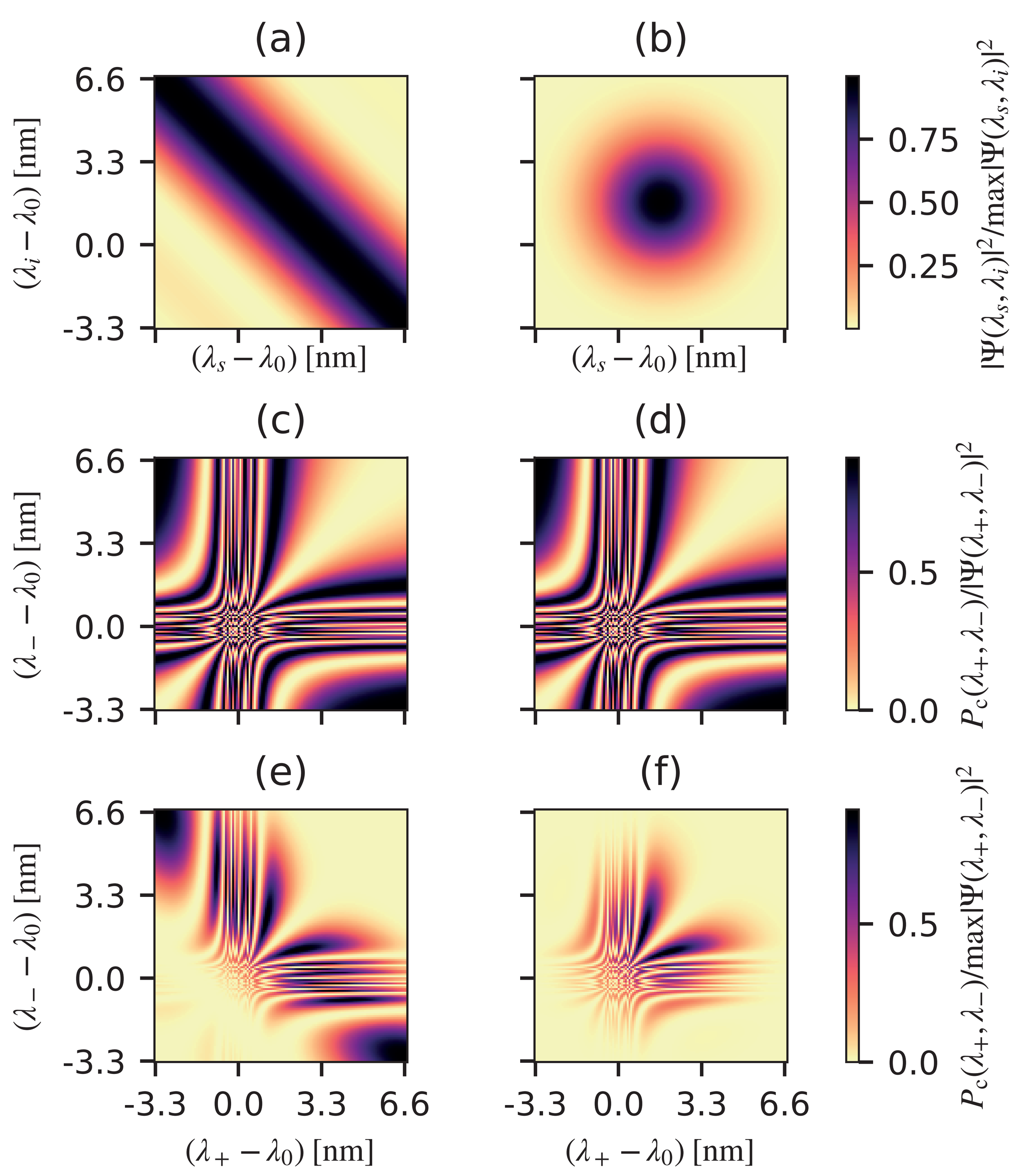


Coincidence maps are a combination of the joint spectral intensity (JSI) of the employed two-photon states and the patterns resulting from spectrally-resolved two-photon interference.

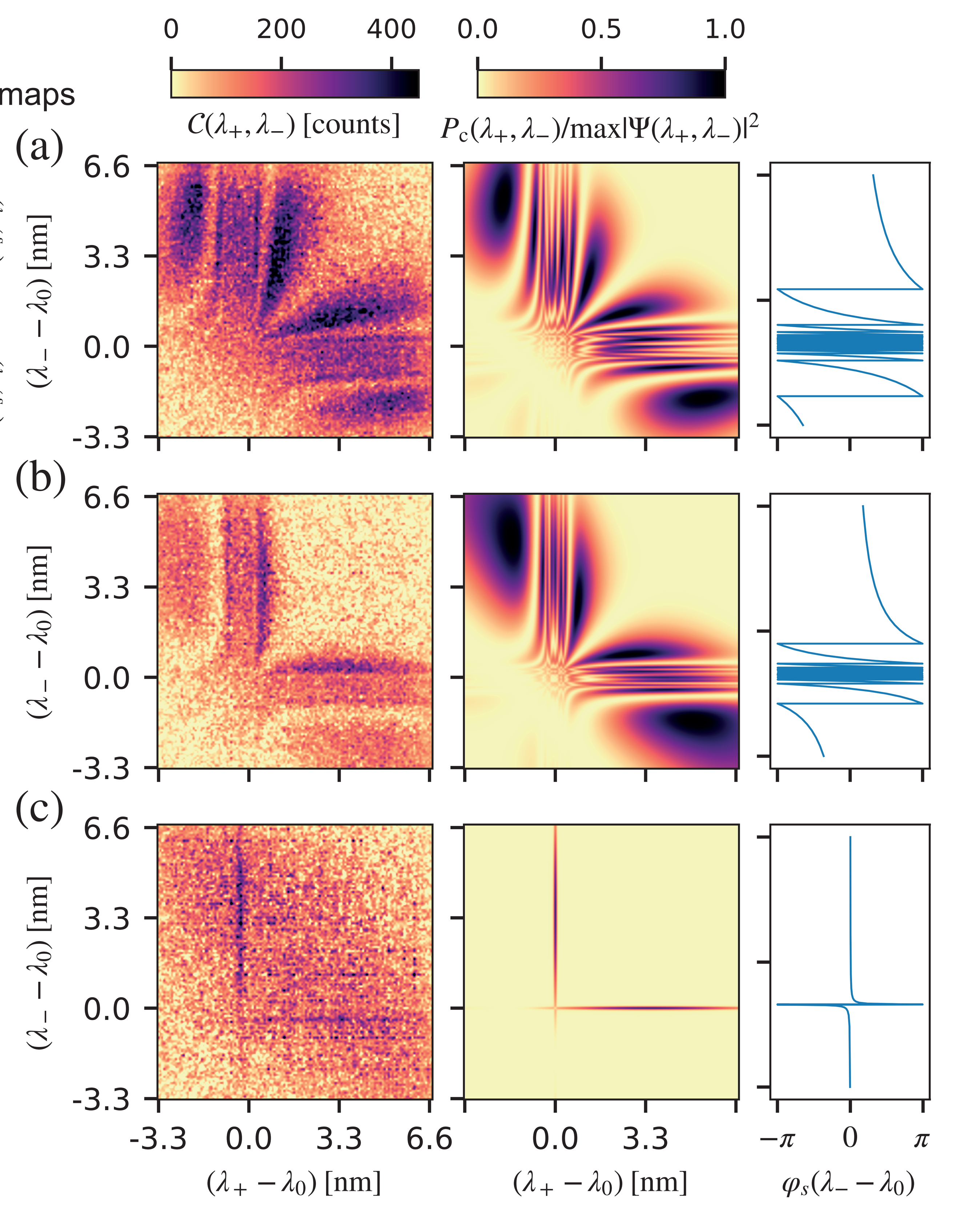
Left - simulation of spectrally correlated photons case (experimental);

Right - simulation of uncorrelated photons case;

(a),(b) - JSI; (c),(d) - interference patterns; (e), (f) - final maps



Experimental results (left column) for different temperatures of the Rb vapor cell (a) 188 °C, (b) 174 °C, (c) 86 °C match the fitted theory prediction (center). Right column represents fitted spectral phase. Optical depths are from 4.6e3 to 20.



$$P_c(\lambda_+,\lambda_-) = \frac{1}{4}|\Psi(\lambda_+,\lambda_-) - \Psi(\lambda_-,\lambda_+)|^2$$

$$P_c(\lambda_+,\lambda_-) = \frac{1}{2}[1-\cos(\varphi_s(\lambda_+) - \varphi_s(\lambda_-))] \times |\Psi(\lambda_+,\lambda_-)|^2$$

$$\varphi_s(\lambda) = \mathrm{OD} \times \frac{x(\lambda)}{1+x(\lambda)^2} \qquad x(\lambda) = 2\pi\tau c(\lambda-\lambda_0)/\lambda_0^2$$

Lorentzian resonance profile centered on the $\lambda_0 = 795$ nm D1 Rb line

c - speed of light

τ - Doppler-broadened lifetime of the excited state (215 ps to 240 ps for the temperature range)

Fast single photon detection

A custom camera has been designed and built in our lab [4], specifically for the fast (82 000 fps this experiment) LUX2100 sensor. Interfacing the camera chip is done via programmable logic (field programmable gate array FPGA) that ensures fast transfer of camera frames as well as provides low-level real-time image processing and photon localization. The FPGA chip (Zynq-7020) has an ARM processor on-board which provides an interface between the low-level logic and custom Python software on the PC site.

[1] Chrapkiewicz *et al.*, Nat. Photonics **10**, 576–579 (2016)

[2] L.S. Costanzo *et al.*, Phys. Rev. Lett. **116**, 023602 (2016)

[3] Lipka *et al.*, arXiv:2105.02795 (2021)

[4] Lipka *et al.*, Opt. Lett. **46**, 13, 3009-3012 (2021)

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