Temporal imaging for atomic single-photon systems

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Abstract: We demonstrate temporal far-field imaging based on ac-Stark spatial spin-wave phase modulation in a gradient echo memory. We achieve resolution of 20 kHz with MHz-level bandwidth and ultra-low noise enabling operation in the single-quantum regime.
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1. Introduction

Plenty of quantum information protocols are enabled by manipulation and detection of photonic spectro-temporal degrees of freedom via light–matter interfaces. Feasible implementations of protocols merging the flexibility of atomic systems and temporal processing capabilities inherently require an ability to manipulate and detect temporal photonic modes with spectral and temporal resolution matched to the narrowband atomic emission. A versatile approach leveraging spectro-temporal duality, is to perform a frequency to time mapping—a Fourier transform—in an analogy with far-field imaging in position-momentum space. State-of-the-art solutions for temporal imaging and bandwidth conversion are all well suited for >100 GHz bandwidths, corresponding to emission from quantum dots or other solid-state systems. In principle, the techniques based on electro-optic modulation [1] or four-wave mixing and highly-dispersive fibers [2] could allow for matching broadband light to narrowband systems based on atoms, color centres or optomechanics. In practice, however, such large enough dispersions cannot be efficiently realized and techniques of temporal imaging for narrowband systems do not currently exist.

2. Results

Fig.1. Experimental sequence for far-field temporal imaging. (a) Time-trace of the Zeeman shift gradient β used in the GEM protocol, allowing two-directional mapping of signal frequencies to distinct positions in the atomic cloud. (b) Control field (red) and spin-wave spatial modulation (SSM, yellow) laser pulse sequence divided into three stages corresponding to lens–propagation–lens operations. The lens (1) is implemented during the GEM writing process by a chirped control field. (2) The 3 μs long SSM laser pulse imprints a parabolic phase profile onto
the stored atomic coherence, which realizes the spectro-temporal free-space propagation. During this stage, the magnetic field gradient is reversed, allowing remapping the coherence to light. (3) Finally, the control field is turned on and the coherence is read out from the memory. (c) Example results for two pulses as inputs. Gray bins represent single photon counts. Red line corresponds to the numerical simulation. (d) Normalized modulus square of atomic coherence in Fourier space. The insets (i) show experimentally obtained linear dependency of the time delay $\Delta t$ (in $\mu$s) on the signal modulation frequency $f$ (in MHz) defined on panel (c).

In this work [3], we demonstrate a novel, single-photon compatible and high-spectral-resolution approach to far-field temporal imaging working in a previously unexplored regime of narrowband atomic emission. Our method is based on inhomogeneously-broadened high-optical-depth cold-atomic medium serving as a gradient-echo quantum memory [4]. We use a recently developed spin-wave modulation technique [5, 6] to effectively engineer a large group-delay dispersion for an optical pulse stored as a spin wave. In a combination with a simple acousto-optic modulation of the control field, we realize a temporal imaging for a 1 MHz bandwidth with a resolution of $\sim$20 kHz, exemplified by observing temporal interference of pulse trains (see Fig.1). The efficiency of our system reaches $\sim$25% and its very low noise equivalent to 0.023 photons allows for operation in the quantum regime.

The device may also serve as a single-photon-level ultraprecise spectrometer for atomic emission, enabling characterization of spectro-temporal, high-dimensional entanglement generated with atoms. Additionally, our technique applied to systems with a higher absorption bandwidth [7] or optical depth [8] can bridge the bandwidth gap to enable hybrid solid-state–atomic quantum networks operating using the full temporal-spectral degree of freedom.

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