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Coherent control of optical information with matter wave dynamics

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In recent years, significant progress has been achieved in manipulating matter with light, and light with matter[1]. Resonant laser fields interacting with cold, dense atom clouds provide a particularly rich system[2–6]. Such light fields interact strongly with the internal electrons of the atoms, and couple directly to external atomic motion through recoil momenta imparted when photons are absorbed and emitted. Ultraslow light propagation in Bose–Einstein condensates[7] represents an extreme example of resonant light manipulation using cold atoms. Here we demonstrate that a slow light pulse can be stopped and stored in one Bose–Einstein condensate and subsequently revived from a totally different condensate, 160 μm away; information is transferred through conversion of the optical pulse into a travelling matter wave. In the presence of an optical coupling field, a probe laser pulse is first injected into one of the condensates where it is spatially compressed to a length much shorter than the coherent extent of the condensate. The coupling field is then turned off, leaving the atoms in the first condensate in quantum superposition states that comprise a stationary component and a recoiling component in a different internal state. The amplitude and phase of the spatially localized light pulse are imprinted on the recoiling part of the wavefunction, which moves towards the second condensate. When this 'messenger' atom pulse is embedded in the second condensate, the system is re-illuminated with the coupling laser. The probe light is driven back on and the messenger pulse is coherently added to the matter field of the second condensate by way of slow-light-mediated atomic matter-wave amplification. The revived light pulse records the relative amplitude and phase between the recoiling atomic imprint and the revival condensate. Our results provide a dramatic demonstration of coherent optical information processing with matter wave dynamics. Such quantum control may find application in quantum information processing and wavefunction sculpting.

In our experiments, two Bose–Einstein condensates[8–10] (BECs) of approximately 1.8×10^6 sodium atoms each, and separated by more than 100 μm, are created in a double-well trapping potential in internal energy state $|1\rangle$(Fig. 1a). The trapping potential is abruptly turned off, and after 1 ms, the atoms are illuminated with a 'coupling' laser beam resonant with their internal $|2\rangle \rightarrow |3\rangle$ transition and travelling in the $-z$ direction (Fig. 1a, b). A counter-propagating, 3 μs gaussian 'probe' laser pulse, resonant with the $|1\rangle \rightarrow |3\rangle$ transition, is then injected into the first BEC. The laser beams drive the atoms into coherent superposition 'dark' states with destructively interfering absorption amplitudes such that neither probe nor coupling laser is absorbed[11–13]. The propagating light pulse creates a slight atomic polarization that slows and spatially compresses the pulse by a factor of 5×10^7 (refs 7, 14, 15). Ultimately, the light pulse is completely contained within the condensate[16].

With $\psi_i(\mathbf{R}, t)$, $(i = 1, 2, 3)$ representing the three components of an atom's external wavefunction at time t and position $\mathbf{R}$, the dark state superposition is $\Psi_D(\mathbf{R}, t) = \psi_1(\mathbf{R}, t)|1\rangle + \psi_2(\mathbf{R}, t)|2\rangle$, where the amplitude and phase of the state $|2\rangle$ component relative to the state $|1\rangle$ component are determined by the amplitude and phase of the probe electric field, $\mathbf{E}_p(\mathbf{R}, t) = \frac{1}{2}\mathcal{E}_p(\mathbf{R}, t)e^{i(\mathbf{k}_p \cdot \mathbf{R} - \omega_p t)} + \text{c.c.}$ (where c.c. is the complex conjugate), relative to the coupling electric field, $\mathbf{E}_c(\mathbf{R}, t) = \frac{1}{2}\mathcal{E}_c(\mathbf{R}, t)e^{i(\mathbf{k}_c \cdot \mathbf{R} - \omega_c t)} + \text{c.c.}$, according to[17]:

$$\frac{\psi_2(\mathbf{R}, t)}{\psi_1(\mathbf{R}, t)} = -\frac{\Omega_p(\mathbf{R}, t)}{\Omega_c(\mathbf{R}, t)} e^{i(\mathbf{k}_p - \mathbf{k}_c)\cdot \mathbf{R} - i(\omega_p - \omega_c)t} \quad (1)$$

Here, $\Omega_p(\mathbf{R}, t) = \mathbf{d}_{31} \cdot \mathcal{E}_p(\mathbf{R}, t)/\hbar$ and $\Omega_c(\mathbf{R}, t) = \mathbf{d}_{32} \cdot \mathcal{E}_c(\mathbf{R}, t)/\hbar$ are the probe and coupling Rabi frequencies, where $\mathbf{d}_{jk} = -e\langle j|\mathbf{r}|k\rangle$ are electric dipole matrix elements, $\mathcal{E}_{p,c}$ are the slowly varying envelopes of the laser fields, $-e$ is the electron charge, and $\hbar$ is Planck's constant. In the present experiment, the anti-parallel orientation of the probe and coupling wavevectors, $\mathbf{k}_p$ and $\mathbf{k}_c$, produces phase variation in the dark state on optical length scales.

According to equation (1), the variation of ψ_2 in space and time mimics that of the probe light pulse such that a slowly varying envelope of ψ_2 accompanies that of the highly compressed, slowly moving light pulse through the condensate. With the light pulse thus contained in the condensate, we turn the coupling laser off over 40 ns. As a result, in order to preserve the dark state (equation (1)), the atoms coherently and adiabatically drive the probe light field to extinction, but the dark state imprint of the pulse remains in the atom cloud[16,17,18]. The spatial phase variation impressed on ψ_2 in this process corresponds to a two-photon recoil of $\hbar(k_p + k_c)/m = 59\ \mu\text{m ms}^{-1}$, where m is the atomic mass. Hence a ψ_2 'messenger' atom pulse is ejected from its initial position[19] in the same direction as the incident light pulse, and ultimately leaves the first condensate and travels as a coherent matter wave towards, through and beyond the second BEC (Fig. 1c).

When this messenger pulse is embedded in the second BEC (for example, 2.1 ms in Fig. 1c), we re-illuminate the system with the coupling laser. Even though the messenger pulse is alien to this second BEC, the atoms cooperatively drive the light pulse back on. The revived light pulse then propagates out of the second condensate under slow light conditions, with the propagation direction $(+z)$ determined by the phase imprinted on the messenger atoms[17]. A light pulse revived after 2.7 ms of messenger flight is detected on a photomultiplier tube, as presented in Fig. 2a.

A comparison of Figs 2a and 3a reveals that a pulse revived in a separate BEC appears qualitatively similar to one revived inside the condensate in which it was stored. Before discussing the physics of light pulse storage and revival in separate BECs, we examine the process for a single atom cloud. Light pulses can be revived in a single BEC up to 0.7 ms after storage, that is, as long as the messenger atom

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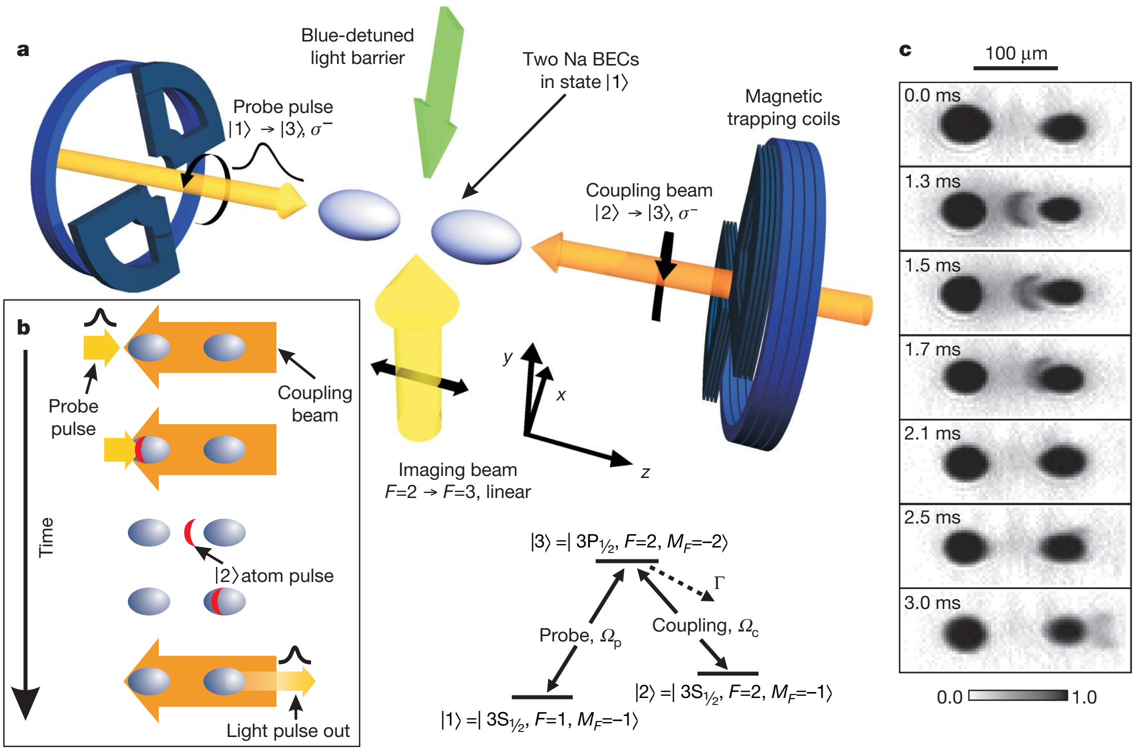

Figure 1 | Diagram of the experiment. a, Two sodium BECs (pale blue) are prepared in state $|1\rangle$ in a double-well potential formed by combining a harmonic magnetic trap (dark blue) and a repulsive optical dipole barrier (focused 532 nm green laser beam with elliptical gaussian cross-section). The entire potential is turned off 1 ms before experiments begin, whereupon the probe (light orange) and coupling (orange) laser beams are introduced. Finally, the condensates are imaged with a laser beam (yellow), near resonance for the atoms' $F=2 \rightarrow F=3$ transition, after optical pumping to $F=2$. **b,** Experiments begin with the injection of a probe laser pulse (light orange) into the first (left) BEC, while the cloud is illuminated by the counter-propagating coupling laser beam (orange). The pulse propagates into the condensate under ultraslow light conditions. After the probe pulse is spatially compressed within the cloud, the coupling beam is switched off, leaving an imprint of the probe pulse's phase and amplitude in the form of atomic population amplitude in state $|2\rangle$ (red). Each atom's $|2\rangle$ component has a momentum corresponding to two photon recoils (absorption from the probe beam and stimulated emission into the coupling beam) and is ejected towards the second (right) BEC. When this 'messenger' atom pulse in $|2\rangle$ arrives, the coupling beam is switched back on, and the probe light pulse is regenerated in the second condensate. Revived light pulses are imaged onto a 50 μm pinhole (to reject background light) and detected with a photomultiplier tube. **c,** Resonant absorption images of BECs and travelling messenger pulse, at indicated times since light pulse storage. No revival coupling beam is fired, and the messenger pulse is observed to travel through and beyond the second BEC.

pulse remains within the condensate. In this case, we can describe the revival of a light pulse as resulting from an interference of each atom's wavefunction with itself. The ψ_2 imprint is much smaller than the extent of the ψ_1 wavefunction and has been translated (owing to two-photon recoil) from its original location (see Fig. 3a inset). During revival, the coupling laser creates some ψ_3 amplitude sourced from the translated ψ_2 imprint, and hence a dipole moment, proportional to $\psi_1^*(\mathbf{R})\psi_3(\mathbf{R})$, is generated in each atom, which drives the probe light field back on. As the system is driven into the dark state, described by equation (1), the ratio between the value of the initial ψ_1 at the storage location and of ψ_1 at the revival position is mapped onto the regenerated light pulse. The ψ_2 imprint is coherently added to ψ_1 at the revival location as the light pulse subsequently leaves the region under slow light conditions. This picture shows that a direct measurement of the one-body density matrix of the atom cloud[20] can be made by recording the revived light pulse energy as a function of the distance between the storage and revival locations. That light pulse revival is possible over the full length of a Bose condensate (Fig. 3a) reflects the condensate's off-diagonal long-range order[21]. In contrast, in the non-condensed atom cloud shown in Fig. 3b, the revived pulse energy decays with a 1/e time of 2.5 μs during which the $|2\rangle$ component travels only 147 nm. This distance is of the order of the thermal de Broglie wavelength and is much less than the extent of the cloud.

When light pulse storage and revival occur in two different atom clouds separated before condensation, as in Fig. 2a, each atom's wavefunction is initially localized to either but not both of the two isolated BECs. Therefore, the dark state superposition imprinted during storage exists only for atoms from the first BEC. Nevertheless, a coherent light pulse can still be revived from the second condensate through bosonic matter wave stimulation. To see how, we use a second quantized description of the matter fields. The interaction between light and matter is governed by the hamiltonian

$$\hat{\mathbf{H}}_{\mathrm{int}} = -\frac{1}{2}\int \mathrm{d}\mathbf{R}(\mathbf{d}_{31}^{*}\cdot\hat{\mathbf{E}}_{\mathrm{p}}^{(-)}(\mathbf{R})\hat{\psi}_1^{\dagger}(\mathbf{R})\hat{\psi}_3(\mathbf{R}) + \mathbf{d}_{32}\cdot\hat{\mathbf{E}}_{\mathrm{c}}^{(+)}(\mathbf{R})\hat{\psi}_3^{\dagger}(\mathbf{R})\hat{\psi}_2(\mathbf{R}) + \mathrm{h.c.}) \quad (2)$$

where $\hat{\psi}_i^{\dagger}(\mathbf{R})$ and $\hat{\psi}_i(\mathbf{R})$ are creation and annihilation operators for an atom in internal state $|i\rangle$ at position $\mathbf{R}$ (ref. 22), and h.c. indicates the hermitian conjugate. Here, we have also expressed the laser fields in second quantized form[23] to stress the symmetry of the matter and light fields discussed below. During revival, when the coupling laser creates a population amplitude in $|3\rangle$ (second term in equation (2)), the presence of a BEC in $|1\rangle$ creates a large rate for bosonic stimulated scattering of atoms into the condensate mode (due to the presence of $\hat{\psi}_1^{\dagger}$ in the first term of equation (2)[24–28]). This bosonic stimulation drives the probe light field on, and the four interaction terms of $\hat{\mathbf{H}}_{\mathrm{int}}$ in combination drive the system into a dark state[17]. In this picture, the coupling laser field and the matter field for atoms in $|1\rangle$ form a perfectly symmetric pair: bosonic stimulation into a macroscopically occupied photon field (the coupling laser) drives coherent dynamics

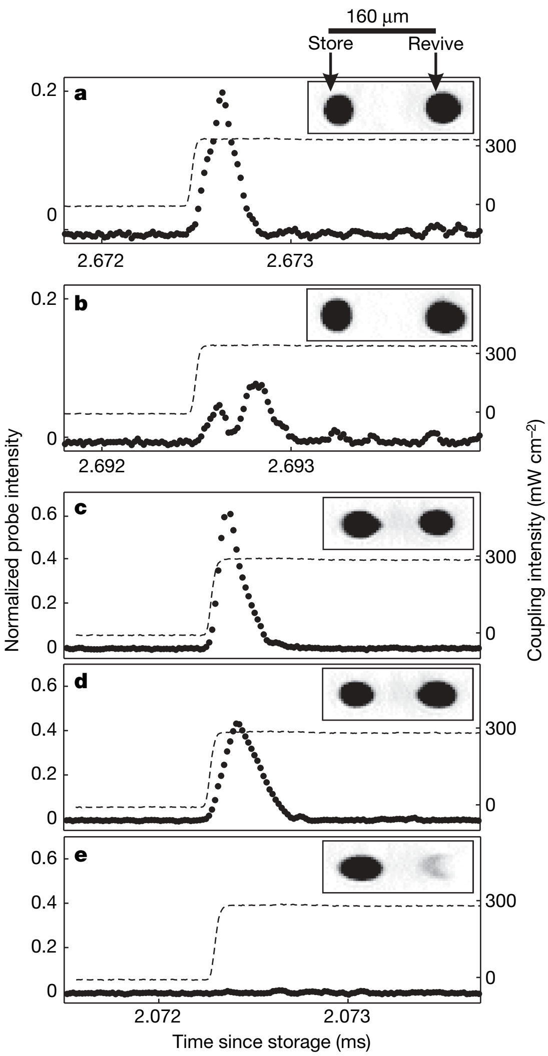

Figure 2 | Light pulse storage and revival in two separate condensates. Revived probe pulses, normalized to input pulse intensity, are plotted against time since pulse storage (dots, left-hand axis), and simultaneously recorded coupling intensity (dashed line, right-hand axis). Insets are resonant absorption images of the $|1\rangle$ condensates, 20 μs after revival. **a**, **b**, Light pulses revived in the second of a pair of independently condensed BECs. Atoms are evaporatively cooled in a 2.3-μK-deep double-well potential formed by a magnetic trap combined with a light barrier (the Bose-condensation temperature is 660 nK). After condensation, the magnetic potential is adiabatically softened to $\omega_z = 2\pi \times 20$ Hz and $\omega_r = 2\pi \times 40$ Hz. Subsequently, the light barrier is adiabatically lowered to 10μ, where μ is each well's resulting chemical potential. The trapping potential is then turned off in less than 200 μs. After 1 ms, the probe pulse is stored in the first BEC ($\Omega_p = 2\pi \times 2.6$ MHz, $\Omega_c = 2\pi \times 2.6$ MHz). In **a**, the light pulse is revived in the second BEC after 2.67 ms during which time the $|2\rangle$ atom pulse travels 157 μm. Note, $\Omega_{c,\mathrm{revival}} = 2\pi \times 21.4$ MHz, resulting in a temporally narrowed output pulse[16]. In **b**, the messenger $|2\rangle$ pulse travels to a different location in the second BEC, where differences in density and phase patterns between the two lead to a bimodal structure. **c**, **d**, Revived light pulses from condensates formed by adiabatically splitting a single magnetically trapped BEC with a 1.5μ-tall light barrier, ramped up over 100 ms, and held constant for 1 s. A typical pulse (**c**) contains 6.9×10^3 photons, 2.2% of the input pulse energy. In **d**, a larger, denser second BEC yields a slower light propagation speed and a broader and less intense pulse, with similar energy to **c**. **e**, A control experiment in which experimental timing and conditions were exactly the same as in **c** and **d**, but with no second BEC.

during the initial light pulse injection, whereas stimulation into a macroscopically occupied matter field (the second $|1\rangle$ BEC) secures coherence during regeneration of the probe light pulse.

Revived light pulses under various conditions are shown in Fig. 2a–d. Whereas the BECs in Fig. 2a and b are condensed in separate potential wells, those in Fig. 2c and d are formed by adiabatically separating an already-formed condensate. We observe no qualitative difference between revivals in a single condensate (Fig. 3a), in adiabatically formed condensate-pairs (Fig. 2c, d), or in condensates that have always been separate (Fig. 2a). In all cases, no atoms are observed when we selectively image state $|2\rangle$ after the probe light pulse has been revived, indicating that the messenger atom pulse has been fully converted to light and state $|1\rangle$ atoms. No revived light pulse is observed when an isolated messenger atom pulse is illuminated with the coupling field (Fig. 2e).

It should be stressed that for light pulse revival to succeed with two distinct atom clouds as described, the atoms in both clouds must be Bose-condensed. The rate of coherent emission events in the revival process is determined by the Bose stimulation factor, $\hat{\psi}_1^\dagger\hat{\psi}_1$, for scattering into the second condensate. For a macroscopic occupation of this condensate, the stimulated processes completely dominate the spontaneous ones. By contrast, if the atoms formed a degenerate Fermi gas, attempts at revival in the second cloud would lead to emission rates below even the spontaneous rate obtained from a non-condensed, bosonic cloud[27,28]. It should also be noted that the two independently created condensates used in the experiments for light pulse storage and revival have a completely random relative phase. Therefore, interference experiments in which the revived light pulse interferes with a reference pulse would lead to high-contrast interference in each shot, but with random absolute fringe position.

Figure 2b shows a bimodal revival pulse obtained under the same conditions as in Fig. 2a, except that we let the messenger atom pulse propagate to a different location in the second $|1\rangle$ condensate before the light pulse is revived. Between storage and revival times, coherent atom dynamics create phase gradient differences and a different

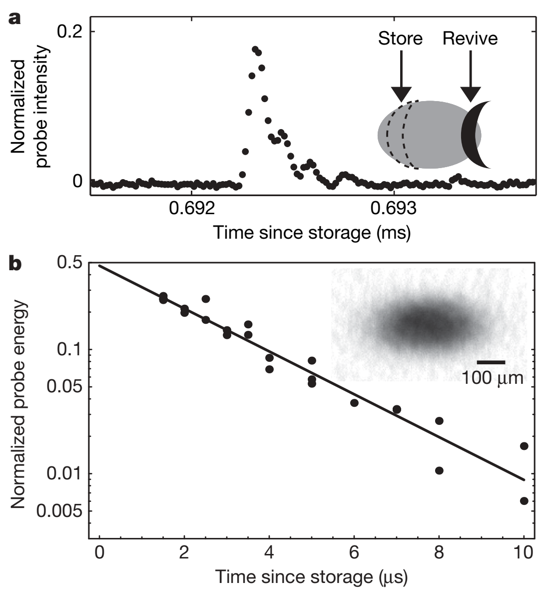

Figure 3 | Light pulse revivals in single clouds. **a**, A light pulse is revived at the right end of a single BEC of 3.4×10^6 atoms, 0.69 ms after storage in the left end. The cloud was prepared in a harmonic magnetic trap ($\omega_z = 2\pi \times 20$ Hz, $\omega_r = 2\omega_z$). All light parameters are similar to those in Fig. 2. **b**, Decay of revival signal in thermal cloud. The energy of the revived light pulse is plotted as a function of time since pulse storage. The thermal cloud (inset) has 13.5×10^6 atoms at 470 nK, just above the critical temperature for BEC (340 nK) in the trap described in **a**. Input probe Rabi frequency is $2\pi \times 3.2$ MHz; coupling storage and revival Rabi frequencies are $2\pi \times 3.5$ and $2\pi \times 17.5$ MHz, respectively.

position-dependent density ratio between the messenger and second $|1\rangle$ BEC. This determines the structure of the revived light pulse, as we have confirmed by numerical simulations.

These observations demonstrate coherent processing of optical information. In the experiments, expansion dynamics due to repulsive atom–atom interactions in the condensates after trap turn-off create $\sim 0.5\,\mathrm{rad}\,\mu\mathrm{m}^{-1}$ phase variations during the storage time. As controlling the revival time to within tens of microseconds controls the propagation depth of the messenger atom pulse to micrometre precision, we can revive the light pulse at locations where the phase patterns of the messenger and second BEC match. This leads to revived light pulses with the same shape as the incoming light pulse (Fig. 2a). For other propagation distances of the messenger pulse, various phase patterns can be imprinted on the revived light pulse, and differently shaped revival pulses are recorded at the photomultiplier. This coherent processing could be delicately controlled in trapped condensates, for example, by way of manipulation of atomic scattering lengths with Feshbach resonances[17].

Loss of $|2\rangle$ amplitude in the messenger pulse from atom–atom scattering[29,30], together with a roughly 50% loss from light pulse propagation in the condensate before storage, account for the difference in energy between the incident and the revived light pulses; there are no detectable losses from the storage and revival processes themselves. By careful selection of atomic species, magnetic sublevels, and manipulation of scattering lengths, we could minimize both slow light and atom pulse propagation losses. Shaping the density profile of the $|1\rangle$ condensates could increase the optical bandwidth of the process and further minimize losses.

We have observed the retrieval of optical information from a BEC after optical storage in a completely separate BEC. This is a result of slow-light-mediated atomic matter-wave amplification, which fully converts and coherently adds a messenger pulse of state $|2\rangle$ atomic amplitude to a receiving $|1\rangle$ condensate. Coherent atom pulses could repeatedly be moved from one condensate to another, which could be used as a replenishing scheme in a continuous-wave atom laser. The system also forms the basis for a new type of interferometer where spatially selected parts of an atomic wavefunction interfere. As demonstrated for bosons, such interferometry can be used for measurements of off-diagonal long-range order in spatially selected regions of degenerate gases of fermions and bosons.

We have demonstrated coherent optical information processing with matter wave dynamics: optical information is imprinted on a Bose-condensed atom cloud, quantum coherent atom dynamics alter the atomic imprint during the storage time, and finally the result is written back onto propagating optical fields. This points to a number of avenues in classical and quantum information processing. As a messenger atom pulse that embodies the incident light travels in free space, it can be independently trapped—potentially for minutes—and manipulated with external fields. Resulting classical and quantum states of the atom pulse can then be mapped onto revived light fields[17]. With the large optical delay-bandwidth products of $\sim 10^3$–10^4 already obtained here, this could also lead to novel designs for dynamically controllable optical delay lines.

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