A subwavelength atomic array switched by a single Rydberg atom

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Enhancing light–matter coupling at the level of single quanta is essential for numerous applications in quantum science. The cooperative optical response of subwavelength atomic arrays has been found to open new pathways for such strong light–matter couplings, while simultaneously offering access to multiple spatial modes of the light field. Efficient single-mode free-space coupling to such arrays has been reported, but spatial control over the modes of outgoing light fields has remained elusive. Here, we demonstrate such spatial control over the optical response of an atomically thin mirror formed by a subwavelength array of atoms in free space using a single controlled ancilla atom excited to a Rydberg state. The switching behaviour is controlled by the admixture of a small Rydberg fraction to the atomic mirror, and consequently strong dipolar Rydberg interactions with the ancilla. Driving Rabi oscillations on the ancilla atom, we demonstrate coherent control of the transmission and reflection of the array. These results represent a step towards the realization of quantum coherent metasurfaces, the demonstration of controlled atom–photon entanglement and deterministic engineering of quantum states of light.
the cooperative array allows for coherent switching between various spatial light modes, such as the transmission and reflection of an atomic array. Furthermore, the cooperative optical response of ordered arrays dramatically reduces the atom number and density required to reach optical depths comparable to disordered ensembles\(^{27,29}\). Similar to recent work performed in optical cavities\(^{36}\), they can therefore help to mitigate known systematics that limit the performance of disordered ensembles in free space at large atomic densities\(^{35,36}\).

Here, we exploit the strong cooperative response of an array of ordered emitters separated by subwavelength distances to realize a switch for photons. This setup allows for recreating the prototypical situation encountered in strongly coupled cavity quantum electrodynamics, where single-atom control can be exploited to reroute single photons\(^{4}\). We utilize the strong interactions between Rydberg states of opposite parity to switch the optical properties of the array from transmitting to reflecting. We achieve spatial control by using an ancilla atom prepared with single-site precision at a specific target position within the array. We demonstrate that the optical properties of the array can be altered coherently by driving Rabi oscillations on the ancilla into the Rydberg state. Finally, we directly measure the spatial switching area of the ancilla in our system and present evidence that the residual imperfections in switching are dominated by the finite Rydberg lifetime and preparation fidelity of the ancilla, both straightforward to overcome with future upgrades to the experimental setup.

Analogous to recent experiments focused on quantum optics with Rydberg atoms\(^{11,37}\), the key idea for controlling our subwavelength array is to transfer the strong interactions between Rydberg states to the optical response of the cooperative array through electromagnetically induced transparency (EIT)\(^{36}\). We start with a cooperative atomic array with emitters approximately described as two-level systems with ground state \(|g\rangle\) and excited state \(|e\rangle\). To induce EIT, the excited state \(|e\rangle\) is coupled with a control field \(\Omega_c\) to a highly excited Rydberg \(S\)-state \(|S\rangle\) (Fig. 1B). As a result, the cooperative optical two-level response for a weak probe field of Rabi frequency \(\Omega_p\) impinging normal on the array, is altered and the system becomes transparent on the \(|g\rangle \rightarrow |e\rangle\) resonance in the presence of the control beam (Fig. 1C, middle column). In establishing transparency, the excited state \(|S\rangle\) is admixed to the state \(|e\rangle\) through the control field \(\Omega_c\). Consequently, \(|e\rangle\) inherits some of the long-range interacting character of \(|S\rangle\). The parameters \(\Omega_c\) and \(\Omega_p\) are chosen to keep the Rydberg state population sufficiently small to avoid optical nonlinearities due to self-blockade, which is expected when the probability to find any array atom in \(|S\rangle\) approaches unity\(^{36,39}\). To control the properties of the cooperative mirror, an additional ‘ancilla’ atom in the ground state \(|g'\rangle\) is excited to a neighbouring Rydberg \(P\)-state \(|P\rangle\).

Due to strong Rydberg interactions between \(|S\rangle\) and \(|P\rangle\), the state \(|S\rangle\) is shifted in energy by \(U_m(r)\). This interaction shift exceeds half of the EIT spectral width within a ‘blockade disc’ of radius \(r_b\) (refs.\(^{40,41}\)) centred around the location of the ancilla. Consequently, the EIT condition breaks down and the optical properties return to those of the cooperative mirror. Due to its coherent nature, the single ancilla atom can entangle the mirror response with the ancilla state, which can
superfluously be exploited for photonic state engineering. Furthermore, controlling the position of the ancilla atom within the array enables full spatial control over the optical properties of the array (Fig. 1c). In particular, using this scheme, optical modes with diameters of a few lattice sites can be controlled without compromising the cooperativity of the response.

We began our experiments by preparing a nearly unity filled two-dimensional atomic array of $^{87}$Rb atoms spin-polarized in the state $|g⟩ = |5S_{1/2}, F = 2, m_F = -2⟩$ in a single vertical antinode of a three-dimensional optical lattice with lattice constant $a_0 = 332$ nm. The lattice spacing was below the transition wavelength $\lambda_g = 780$ nm from the ground state $|g⟩$ to the excited state $|e⟩ = |5P_{3/2}, F = 3, m_F = -3⟩$ leading to a cooperative response of the array at a ratio of $a_w/\lambda_g = 0.68$ (ref. 24). To enable control of the optical response of the mirror via Rydberg interactions, we coupled the excited state $|e⟩$ to the $|g⟩ = |4S_{1/2}, m_F = -1/2⟩$ Rydberg state. The optical properties of the array were probed with a weak probe beam with Rabi coupling $\Omega_p/2\pi \approx 168(5)$ kHz $\ll \Omega_p/2\pi = 6.7(6)$ MHz on the $|g⟩ \leftrightarrow |e⟩$ transition, which is sufficient to create the EIT window and admiss a small Rydberg amplitude to the excited state $|e⟩$ (ref. 24). We deterministically created a single ancilla atom in the $|g⟩' = |5S_{1/2}, F = 1, m_F = -1⟩$ state with a fidelity of 0.83(4) at the centre of the array using single-site addressing (ref. 24). The ancilla was then controllably excited to the Rydberg state $|p⟩ = |4P_{3/2}, m_F = 3/2⟩$ on an ultraviolet (UV) transition at a wavelength of 297 nm. The interaction with the admixed $|S⟩$ state Rydberg fraction of the array atoms led to a Förster-enhanced energy shift $U_{\text{Förster}}$, featuring a characteristic van der Waals distance dependence proportional to $C_g/r^6$ due to interactions with nearby Zeeman sublevels (Supplementary Information). For our parameters, this resulted in a blockade radius $r_b = (2C_g/\Gamma_p)^{1/6} = 4.6 \mu$m (Supplementary Information) which defined the range over which the mirror properties are altered. Preparing an atomic array with a radius $r_b \gg r_l$ and detecting the probe light with a low-noise electron-multiplying change-coupled device (EMCCD) camera, we directly reveal the spatially switched area and demonstrate the spatially selective response of our array (Fig. 1c).

In a first set of experiments, we aim to demonstrate the basic mechanism of switching the cooperative mirror by using the ancilla atom. To this end, we first confirm the cooperative nature of our atomic array by measuring the reflection and transmission response of a laser beam tuned near the resonance of the $|g⟩ \leftrightarrow |e⟩$ transition. We find a strong directional signal with a subradiant Lorentzian lineshape and an extracted width of down $\Gamma_p/2\pi = 3.75(14)$ MHz, narrower than the natural linewidth of $\Gamma_p/2\pi = 6.06$ MHz (Fig. 2a). This confirms that our array is in the cooperative regime explored previously. Illuminating the array with both the probe and control fields on resonance, we observe EIT, resulting in a switching from a reflecting to transmitting response of the array (Supplementary Information).
transmittance (frequency and decay time are fixed and taken from a of the oscillation and overall offset as the only fit parameters, while the oscillation b ancilla. The solid lines in |Fig. 3| cooperative response after a coherent drive of the ancilla. a, Ancilla |g′⟩ ↔ |P⟩ Rabi oscillations obtained from ground state |g′⟩ fluorescence detection by varying the length of the UV pulse before probing (see Fig. 1c for the protocol). Applying a damped sinusoidal fit, we find a Rabi frequency of Δω/2π = 1.22(2) MHz and a decay constant of τ_e = 6(3) μs. The transmittance (b) and reflectance (c) data follow the Rabi oscillation of the ancilla. The solid lines in b and c represent the best fit results, with the amplitude of the oscillation and overall offset as the only fit parameters, while the oscillation frequency and decay time are fixed and taken from a. The three insets in c indicate spatially averaged reflection images for Δω/2π = 0, π and 2π, respectively, with an indicated region of interest of 3 μm × 5 μm. The dashed line in b illustrates the expected transmission signal for an ancilla Rydberg fraction of P_R = 0.96. The solid grey line represents the resonance reflection signal (0.16(3)) from isotropic scattering. The latter was measured experimentally by introducing vertical disorder by means of Bloch oscillations (Supplementary Information). The measurements are averages over 120–170 independent repetitions. Error bars denote the s.e.m.

the single-particle limit of τ_e/2. Our parameters were chosen to maximize the on-resonance contrast between the cooperative mirror and the EIT response using a probe duration τ_p = 20 μs, only slightly shorter than the measured lifetime τ_e = 27(5) μs of the Rydberg ancilla. The probe power and pulse duration were chosen to keep the Rydberg admixture and the effects of self-blockade small, while providing sufficient signal-to-noise ratio of the probe light on the EMCCD camera (Supplementary Information).

To investigate the effect of the Rydberg ancilla on the array, we apply a π pulse on the |g′⟩ → |P⟩ transition with duration t, such that Δω/2π = π. The resulting spectra exhibit a broad resonance featuring a substructure of three distinct peaks, with the reflectance on resonance amounting to 0.25(2) (Fig. 2b). Our observation of a triple-peak structure can be understood to arise from a combination of the configurations with and without the ancilla Rydberg atom present. A simplified model assuming a statistical mixture of the mirror in the switched and unswitched state, weighted with the probability of finding the ancilla in the Rydberg or ground state, respectively, quantitatively reproduces the observed features in Fig. 2b. The ansatz of a statistical mixture of the two mirror states is motivated by imperfect initial state preparation of the ancilla in |g′⟩; and decay of the ancilla Rydberg state during probing (Supplementary Information). To illustrate potential improvements in an upgraded experimental setup, the dashed lines in Fig. 2b also show the expected spectra for perfect ancilla preparation in |g′⟩ and substantially shorter probe duration of τ_p = 2 μs, for which on the order of one photon is scattered, and the decay of the Rydberg ancilla becomes negligible.

To highlight the capability of coherent manipulation in our system, we next aim to dynamically change the optical properties of the atomic array. To this end, we drive the ancilla from the ground state |g′⟩ to the Rydberg state |P⟩ with variable UV pulse durations, resulting in coherent Rabi oscillations of the ancilla with a Rabi frequency of Δω/2π = 1.22(2) MHz (Fig. 3). Measuring the transmittance or reflectance of the array in the same sequence, we find a strong correlation between ancilla Rabi oscillations and the optical properties of the array, where the mirror switches from transmitting to reflecting during the course of the oscillations. Fitting the dynamics of transmittance and reflectance of the array with a damped sinusoidal function derived from the Rabi oscillations with the amplitude and offset of the oscillation as free parameters, we find excellent agreement between this model and the data. This agreement indicates that, indeed, the switching behaviour is determined by the quantum state of the ancilla before probing. The small distortions in the transmittance can be attributed to a non-vanishing probability to initially have two ancilla atoms before excitation to the Rydberg state (Supplementary Information). Notably, the maxima of the oscillating reflectance are clearly above the single-particle limit of a vertically disordered array (ref. 15 and Supplementary Information) demonstrating that the cooperative response of the mirror is preserved during the oscillation (Fig. 3c).

The strong correlation between the state of the ancilla and the state of the mirror can be further studied through photon number statistics. In the ideal case, we expect all photons within a detection window to be reflected (transmitted) when the ancilla is excited to the Rydberg state |P⟩ (in its ground state |g′⟩). We study this correlation by monitoring the number of reflected photons for a longer integration time of τ_e = 60 μs after controllably exciting the ancilla with a π pulse (Fig. 4). The distribution with the ancilla in |P⟩ exhibits a long tail at high...
numbers of reflected photons in addition to a peak at low photon numbers. We find good agreement of our observed histogram with a model taking into account our estimated preparation fidelity as well as the independently measured lifetime of the Rydberg-excited ancilla via Monte Carlo sampling (Supplementary Information and Fig. 4).

The spatial control over the position of the ancilla allows for a fundamentally new approach to controlling the optical response of the subwavelength array in a spatially resolved way. To demonstrate such control, we prepared the ancilla at a target site in the centre of the array and compared the optical response of a small array of radius $r_a = 4.7(7)\,\mu m$ with a large array with radius of $r_a = 12.5(5)\,\mu m$, which exceeds the expected blockade radius (Fig. 5). In the small array, we observe a relatively sharp edge where the transmittance jumps from its central value of 0.48(2) to near unity, due to the combination of the finite size of the array $r_a$ and the blockade radius $r_b$. In contrast, the large array has an increased transmittance at the centre as well as a more gradual increase of the transmittance beyond the blockade radius. These observations indicate the presence of previously studied long-range exchange processes $^{33-36}$, which cause the ancilla to delocalize over the entire system and lead to a smoothened transmission signal. Importantly, these exchange processes can be suppressed either by operating on shorter probe timescales or by reducing the probe power, as the relevant exchange process scales with $\propto 1/N^2$ (ref. $^{44}$ and Supplementary Information). This regime is experimentally accessible with optimized detectors matched to the manipulated spatial modes of the light field, which, however, would not have allowed for the spatially resolved proof-of-principle characterization of the array response performed in this work.

In conclusion, we have demonstrated the ability to switch and coherently control the optical properties of a cooperative subwavelength array of atoms using a single ancilla atom. Our system is presently limited by finite preparation efficiencies as well as the finite Rydberg lifetime of the ancilla. The former can be improved by better addressing techniques, for example, by placing the ancilla in a single microtrap overlapped with the cooperative array, and the latter with optimized single-photon detectors. Alternatively, we foresee the use of Rydberg dressing $^{36}$ for the ancilla, improving its lifetime while minimizing motional decoherence effects due to reduced repulsion in the lattice and the suppression of dipolar exchange processes.

Our measurements already demonstrate all the experimental building blocks to control single photons by manipulating single atoms in subwavelength arrays and open the path towards the detection of atom–photon entanglement $^{46}$, the realization of photon–photon gates $^{28,47}$ or multimode quantum optics in cooperative arrays $^{28-30}$.

### Online content

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Data availability
All presented data are publicly available under https://doi.org/10.17617/3.PNRURG.

Code availability
The code used to analyse the data is available upon reasonable request.

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Author contributions
K.S. acquired the data and, together with P.W., D.W. and D.A., maintained and improved the experimental setup. P.W. and S.H. contributed the theoretical simulations. I.B. and J.Z. supervised the study. All authors worked on the interpretation of the data and contributed to the final manuscript.

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