A subradiant optical mirror formed by a single structured atomic layer

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Versatile interfaces with strong and tunable light–matter interactions are essential for quantum science because they enable mapping of quantum properties between light and matter. Recent studies have proposed a method of controlling light–matter interactions using the rich interplay of photon-mediated dipole–dipole interactions in structured subwavelength arrays of quantum emitters. However, a key aspect of this approach—the cooperative enhancement of the light–matter coupling strength and the directional mirror reflection of the incoming light using an array of quantum emitters—has not yet been experimentally demonstrated. Here we report the direct observation of the cooperative subradiant response of a two-dimensional square array of atoms in an optical lattice. We observe a spectral narrowing of the collective atomic response well below the quantum-limited decay of individual atoms into free space. Through spatially resolved spectroscopic measurements, we show that the array acts as an efficient mirror formed by a single monolayer of a few hundred atoms. By tuning the atom density in the array and changing the ordering of the particles, we are able to control the cooperative response of the array and elucidate the effect of the interplay of spatial order and dipolar interactions on the collective properties of the ensemble. Bloch oscillations of the atoms outside the array enable us to dynamically control the reflectivity of the atomic mirror. Our work demonstrates efficient optical metamaterial engineering based on structured ensembles of atoms and paves the way towards controlling many-body physics with light and light–matter interfaces at the single-quantum level.

Cooperative optical effects in arrays of quantum emitters can be understood as resulting from the coherent scattering of photons between the emitters, or, equivalently, from optical dipole–dipole interactions. Such interactions can result in drastic changes of the optical response of a suitably structured medium, a phenomenon known asDicke super- or subradiance when the entire ensemble of atoms is confined to regions in space that are much smaller than the wavelength of light. For subradiant modes, light can effectively be trapped and stored in free space. Through spatially resolved spectroscopic measurements, we show that the array acts as an efficient mirror formed by a single monolayer of a few hundred atoms. By tuning the atom density in the array and changing the ordering of the particles, we are able to control the cooperative response of the array and elucidate the effect of the interplay of spatial order and dipolar interactions on the collective properties of the ensemble. Bloch oscillations of the atoms outside the array enable us to dynamically control the reflectivity of the atomic mirror. Our work demonstrates efficient optical metamaterial engineering based on structured ensembles of atoms and paves the way towards controlling many-body physics with light and light–matter interfaces at the single-quantum level.

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dipoles are close enough, each dipole $\mathbf{d}_i = a(\mathbf{E}_0(\mathbf{r}) + \mathbf{E}_x(\mathbf{r}))$ is driven by the external field $\mathbf{E}_0$ and the scattered field from the neighbouring atom, $\mathbf{E}_x(\mathbf{r})$. Depending on the interatomic distance, these two fields interfere either constructively or destructively, leading to a sub- or superradiant response of the composite system, as shown in Fig. 1c. By extending this picture to an ordered array, the scattered field $\mathbf{E}_x(\mathbf{r})$ is replaced by the fields emitted by all neighbouring dipoles. The coupling between the scattered fields and dipoles leads to a collective polarizability of the entire array, making it a new quantum object with a cooperative Lamb shift in the resonance frequency and a modified decay rate from the collective excited state. For an infinitely large two-dimensional (2D) square array, such collective states can be selectively created by choosing the incident angle of the driving field relative to the array[10]. Changing the spacing $a$ of the array leads to a substantial increase in transmittance and a strong photon–photon interaction in the array (see Methods).

Our experiments started with a 2D array of $^{87}$Rb atoms loaded into a square optical lattice (lattice constant $a = 532$ nm) with nearly one atom per site[22]. Optical probing of the array was carried out on an isolated two-level transition in the D$_2$ manifold of $^{87}$Rb (see Methods). The collective response of the array was observed by recording either the forward or the backward scattering of a probing beam, as shown in Fig. 1a,b. In the first configuration, the upper probe beam with field $\mathbf{E}_0$ was first scattered by the atom array, and then the transmitted field $\mathbf{E}_\text{trans}$ was collected and imaged by an objective onto an electron-multiplying charge-coupled device (EMCCD) camera, yielding a transmittance of the array $T = |\mathbf{E}_\text{trans} / |\mathbf{E}_0|^2$. In the second configuration, a probe beam with field $\mathbf{E}_1$ was sent through the objective onto the atoms, and the reflected light field $\mathbf{E}_\text{refl}$ was imaged onto the camera, giving a reflectance of $R = |\mathbf{E}_\text{refl} / |\mathbf{E}_1|^2$. Using the high spatial resolution of the imaging setup, only the scattered light field within the bulk of the atom array was recorded for the following analysis. The array was probed well within the weak-drive regime to avoid saturation effects and subsequent photon–photon interactions in the array (see Methods).

We first identified the spectral response for different spatial geometries of the atom cloud. The two geometries that we compared correspond to (a) an almost-unity-filled 2D array, (b) a vertically randomized three-dimensional (3D) array (see Fig. 2 and Methods). The transmittance and reflectance from these configurations was then probed as a function of the probe laser frequency. For the ordered array (a), the transmission spectra obtained show a pronounced subradiant response with a cooperative linewidth of $\Delta \Gamma / \Gamma_0 = 0.68(2)$ and a residual transmittance of only $T = 0.23(1)$ on resonance (uncertainties denote 1 s.d.). The corresponding reflection measurement exhibits a reflectance of up to $R = 0.58(3)$ and a linewidth of $\Delta \Gamma / \Gamma_0 = 0.66(2)$. The fact that the transmittance and reflectance do not add up to unity ($T + R < 1$) originates from the finite collection angle of our objective, because fields scattered at large angles are not collected by the objective (see Supplementary Information). For configuration (b), we intentionally randomized the positions of the atoms along the vertical direction while keeping their horizontal positions in the array fixed, resulting in the same vertical column density as that of (a). Disrupting the vertical position order of the array leads to a substantial increase in transmittance and a strong
randomized vertical positions. The linewidths become broadened to $R_b = 0.58(3)$ in the reflection spectrum. A 3D array with a linewidth of $\Gamma_a = 4.04(12) \text{ MHz}$ and a strong absorption spectrum and a linewidth of $R = 0.13(1)$, respectively. The dashed lines are reference spectra with the natural linewidth of single atoms. Each spectrum is obtained from an average of 15–30 measurements. The insets illustrate the ordering of the atoms and display the numerically simulated differential cross-section of the field scattered by the atoms, where the black arrow indicates the incident direction of the probe beam. The fits are based on Lorentzian line profiles and the error bars denote the standard error of the mean (s.e.m.). NA, numerical aperture.

The strong difference in the cooperative linewidths for the above configurations confirms that the directly driven subradiant modes require the presence of a spatially ordered 2D array, as expected from the coupled-dipole theory\(^9,10\), whereas the linewidth broadening in the random geometry can be attributed to an inhomogeneous broadening in both resonance frequencies and linewidths of the coupled modes (see Supplementary Information). The large difference in reflectance that we observe for the two cases results from the fact that the 2D subwavelength array exhibits highly directional and collectively enhanced scattering\(^6\). Such enhanced interaction is suppressed between the emitters in the 3D array owing to the randomized positions of the dipoles, leading to weaker induced dipole strengths and reduced collective interferences in the emissions. Besides, additional position-dependent phases along the direction of the probe beam are imprinted onto the collective atomic state, which favours phase-matched emission along the same direction, whereas retro-reflection is suppressed\(^6\) (see differential scattering cross-section in Fig. 2).

To control the effective interaction strengths between the atoms, we varied the filling fraction of the 2D array in the range $\eta = 0.4$–0.9 (see Methods) and characterized the change in the cooperative response. Figure 3b shows the fitted cooperative linewidths from the measured absorption and reflection spectra. For low fillings, the atom array shows a linewidth similar to that of isolated single atoms, whereas for increasing filling the cooperative response of the array becomes increasingly subradiant, with the lowest observed linewidths of the array being $\Gamma/(2\pi) < 4 \text{ MHz}$, less than 65% of the natural linewidth $\Gamma_\text{0}$. In Fig. 3c, we compare the filling-normalized absorptance $A/\eta = (1 - T)/\eta$ and reflectance $R/\eta$. The reflectance per atom increases notably with filling, which can be directly attributed to the cooperative contribution within the directional reflection from the 2D array. The absorptance per atom, however, appears independent of the lattice filling. We attribute this to the stronger high-order diffractions at low fillings, caused by the wavefront distortions in the transmitted field, which lead to larger intensity extinction for the finite numerical aperture of the imaging setup and thus balance the reduction in the cooperative response (see Supplementary Information). We also find a notable shift in the resonance frequency of the array as a function of the filling. The frequency shift for increased fillings originates from the cooperative dipole–dipole interaction effect, and therefore can be identified as the cooperative Lamb shift\(^29\) (see Fig. 3d). All observed signals also agree quantitatively with our simulations of the classical coupled-dipole equations. The simulations include a position spread of each atom in the array of the order of the Gaussian ground-state wave function size (see Supplementary Information).

Using the high degree of control over the atoms in the optical lattice, one can dynamically dissolve and restore the 2D ordering of the atoms and thereby dynamically switch the subradiant response through quantum dynamics. For this, we let the atoms perform Bloch oscillations inside the vertical lattice along the $z$ direction under the action of a small potential gradient, giving rise to an energy difference of $\Delta_z$ between neighbouring lattice sites. The initially localized atoms thereby periodically spread out in the vertical direction and refocus onto the original position at integer multiples of the Bloch period $T_\text{b} = h/\Delta_z = 4.7 \text{ ms}$ for the experimental parameters (see Methods), with $h$ the Planck constant\(^30\).
This results in a periodic change of the geometry from an ordered array in two dimensions to a delocalized array (along the $z$ direction) in three dimensions, with an estimated maximum half-width of $\delta z \approx 2.5a$. The measured reflectance versus the tunnelling time in the tilted lattice is shown in Fig. 4. In the subsequent dynamics, two reflection peaks appear at the times of optimal re-focusing. The reflection becomes considerably suppressed once the atoms slightly tunnel out of the single plane. The measured linewidths at the two reflection peaks are both subradiant. By contrast, the measured linewidths at the first half-period, where the atoms maximally disperse out of the plane, is broadened to a value above the natural linewidth.

Despite the strongly subradiant response of the ordered 2D array, deviations from a perfect array of point-like emitters persist in the experiment, which limits the performance of the atom array as an optical mirror and can be attributed to the finite spread of the atomic wave function in each lattice site. The spread essentially disorders the dipoles from positions in a perfect array along all directions during the photon scattering, leading to weakened cooperative interactions and reduced reflectivity of the atom mirror, as shown in Fig. 5b. One would expect that deeper lattices could improve the reflectivity close to $R = 1$ and reduce the linewidth to $\Gamma/\Gamma_0 = 0.56$ or 0.51, as in the case of a perfect array of similar or infinite size, by reducing the spatial extent of the zero-point motion. However, in the experiment we observe the opposite behaviour, as shown in Fig. 5c, d. When the potential depth of the vertical lattice is increased, the measured linewidth continuously increases as well. This effect can mainly be explained through a motional spreading experienced by atoms in the anti-trapped excited $5^{2}P_{3/2}$ state in the lattice potential, which results in enhanced heating after decaying back to the ground state and in position-dependent shifts of the transition frequency inside each lattice site. Both effects

**Fig. 3** | Cooperative response versus filling fraction in the 2D array.  
**a**, Transmission and reflection spectra for filling fractions of $\eta = 0.44, 0.69, 0.92$ (light to dark), with the vertical axis shifted accordingly. **b**, Fitted linewidths for different fillings. The optical response of the array changes from a linewidth close to that of isolated single atoms at low fillings to strongly subradiant at high fillings. **c**, Normalized optical response for each atom. Whereas the absorbance remains nearly constant, the reflectance shows considerable dependence on the filling fraction, highlighting the cooperative contribution in the directional reflection. **d**, Dependence of the resonance frequency on the filling fraction, revealing the cooperative Lamb shift. In all panels, colour-shaded regions correspond to simulations with positional spreads between 0.054a and 0.14a along the $z$ axis and a fixed spread of 0.054a along the $x$ and $y$ axes. The dashed lines correspond to simulations of ideal point-like scatterers in a perfect array with similar size. Error bars in **a** denote s.e.m. and in **b**–**d** the s.d. of the fitted parameters.

**Fig. 4** | Cooperative response under Bloch oscillation. Starting from a near-unity-filled 2D array, the atomic wave packet periodically oscillates along the vertical direction. The reflectance (blue circles) is collectively enhanced once the atomic wave packet refocuses onto the original 2D plane. The lower height and reduced subradiance of the revival peaks results from the residual curvatures in the potential gradients. The measured linewidth (red squares) clearly shows the dynamical recovering of subradiant response. Error bars denote s.e.m. for reflectance and s.d. for the fitted linewidth.
become stronger for deeper lattices and therefore lead to the breakdown of the cooperative response of the array. A quantitative interpretation of these effects would require a full quantum treatment of the coupling between internal and motional degrees of freedom of the atoms, which is lacking so far. A system in which a trapping laser on a ‘magic’ transition is used—for example, optical lattice clocks31—should not exhibit this heating effect. On the basis of our numerical simulations, we are able to extrapolate the experimental reflectance of the array to $R > 0.8$ in the limit where only a single or a few photons are scattered and heating effects are thus negligible (see Fig. 5b). Larger arrays or probe beams smaller than the array size would reduce detrimental edge effects that are present in the current experiment and should allow one to further increase the reflectance to $R > 0.9$ (see also Supplementary Information).

Our local resolution of the atom array provides an ideal setting to explore collective optical excitation transport, for example, in topologically protected edge states32,33. The highly directional optical scattering properties of an ordered array could facilitate a vast improvement in the error bound of quantum memories2,34. In topologically protected edge states32,33. The highly directional optical scattering properties of an ordered array could facilitate a vast improvement in the error bound of quantum memories2,34. Interactions between the excitations would be engineered by geometric control41 or through nonlinear photon–photon interactions in the array42. Interactions beyond the excitation regime would require a full quantum mechanical many-body treatment, opening the path to interacting many-body physics with optical photons40,42. The flexible platform of atoms in optical lattices allows us to explore all these directions in the future.

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Fig. 5 | Limitations to the cooperative response of the 2D array. 

a, b, Simulated absorptance and reflectance for different positional spreads in an array of similar size as that used in the experiment. The dotted (dash-dotted) lines represent positional spread only along the $x$ ($z$) axis. The dashed line represents the same spread along all three axes. The solid lines (red and blue) represent variable spread along the $z$ axis and a fixed spread of 0.054$a$ along the $x$ and $y$ axes, corresponding to a ground-state spread of 300$E$, lattice depth, with $E_r$ denoting the recoil energy of a single atom. The colour-shaded area and the red and blue solid lines correspond to the parameter region used in the simulation in Fig. 3. The imperfect reflectance ($R$ = 0.95) at the zero-spread limit is a result of the edge effect due to the large beam size used in the simulation (beam waist $w_0$ = 6$a$). As a comparison, the grey solid line represents a simulation with equal spread along all directions and a probe beam with size smaller than that of the 2D array ($w_0$ = 6$a$), with $R$ = 1 at the zero-spread limit. c, d, Cooperative response measured under different vertical lattice depths for a near unity-filled 2D array. Although the filling-normalized absorptance markedly decreases in deep lattices, the measured linewidth signals show reduced subradiance for increasing lattice depths. The depths of the horizontal lattices were fixed at $V_{x,zr}$ = 1,000$E$, during the measurement. Error bars denote the s.d. of the fits.

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Methods
Preparation of the atom array
We started the experiment by selecting a single layer of atoms from a Bose–Einstein condensate loaded into a vertical optical lattice. After that, we ramped up two horizontal lattices to create a Mott-insulating state. Then, we prepared a 2D array of $^{87}$Rb atoms with a maximum filling of $\eta = 0.92$ per lattice site on ~200 lattice sites. All of the atoms were prepared in the motional ground state of the 3D optical lattices and initialized in the ground Zeeman sublevel of $|F = 1, m_F = -1\rangle$, then transferred into the final $|F = 2, m_F = -2\rangle$ state with a microwave sweep. Here $F$ and $m_F$ are the hyperfine and magnetic quantum numbers, respectively. A small stabilized magnetic field of 3.3 G was applied perpendicular to the atomic plane to isolate a two-level response with the possible push-out of the atoms in the $F = 2$ state.

Detection scheme and probe intensity
The optical field at the plane of the 2D atom array was imaged by a high-resolution objective with a numerical aperture of 0.68 and a diffraction limit of about 700 nm. To increase our signal-to-noise ratio for the small probe photon numbers, we electronically binned the EMCCD readout in 8 × 8 pixel clusters, corresponding to an area of ~3.3 lattice sites in the atom plane. The transmission efficiency over the entire imaging path is estimated to be 61%, and the quantum efficiency of the camera is 80%. For the absorption measurements, we used a fluence of about 20 photons per lattice site in the probe beam within a duration of 3 ms. For the reflection measurements, a small fraction (~4%) of the reflection probe beam was reflected by a glass plate and focused onto the imaging path. The finite positional spread is modelled by randomly sampling the dipole positions according to the spatial distribution of the objective, we obtain the reflectance and absorptance. The linewidths, resonance detunings and maximum response amplitudes are determined by performing the calculations for different driving field detunings $\Delta$ (and thus different polarizabilities $\alpha$) and fitting a Lorentzian function. The finite positional spread is modelled by randomly sampling the dipole positions according to the spatial density distribution and averaging the far-field intensities.

Control of spatial geometries
To prepare the vertically randomized array, we started with the near-unity-filled 2D array at $V_{x,y} = 40E_r$ for the horizontal lattices and $V_z = 13E_r$ for the vertical lattice. Then, we suddenly switched off the $z$ lattice to let the atoms expand freely for 1 ms along $z$. Subsequently, we rapidly ramped the vertical lattice depth up to $-16E_r$ to pin the atoms, with $E_r$ the tunnelling rate in the vertical lattice.

Simulation of the electromagnetic response
The simulation results were obtained by directly solving the $\sigma^-$-polarization-projected coupled-dipole equations, $\mathbf{d}_l = a_l(\Delta) \hat{P}_a(\mathbf{E}_p(\mathbf{r}_l)+\sum_j \mathbf{G}(\mathbf{r}_l - \mathbf{r}_j)\mathbf{d}_j)$, with $\mathbf{G}(\mathbf{r})$ the free-space dyadic Green function, yielding the individual dipole moments $\mathbf{d}_l$ for a given driving field $\mathbf{E}_p$. By calculating the far field of the dipole emission pattern $\mathbf{E}_\infty(\mathbf{r}) = \sum \mathbf{G}(\mathbf{r} - \mathbf{r}_j)\mathbf{d}_j$ and of the probe beam within the collection angle of the objective, we obtain the reflectance and absorptance. The linewidths, resonance detunings and maximum response amplitudes are determined by performing the calculations for different driving field detunings $\Delta$ (and thus different polarizabilities $\alpha$) and fitting a Lorentzian function. The finite positional spread is modelled by randomly sampling the dipole positions according to the spatial density distribution and averaging the far-field intensities.

Data availability
The experimental data that support the findings of this study are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability
The simulation results can be generated using the numerical methods described within Methods and Supplementary Information and the computer code developed, which are available upon reasonable request.

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Author contributions
J.R. acquired the data and, together with D.W. and A.R.-A., maintained and improved the experimental setup. D.W. contributed the theoretical simulations. C.G. and I.B. supervised the study. All authors worked on the interpretation of the data and contributed to the final manuscript.

Competing interests
The authors declare no competing interests.

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