Transmission of near-resonant light through a dense slab of cold atoms

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The optical properties of randomly positioned, resonant scatterers is a fundamentally difficult problem to address across a wide range of densities and geometries. We investigate it experimentally using a dense cloud of rubidium atoms probed with near-resonant light. The atoms are confined in a slab geometry with a sub-wavelength thickness. We probe the optical response of the cloud as its density and hence the strength of the light-induced dipole-dipole interactions are increased. The observed features are compared with the prediction of a coupled dipole simulation.

The interaction of light with matter is a fundamental problem which is relevant for simple systems, such as an atom strongly coupled to photons [1–3], as well as for complex materials, whose optical properties provide information on their electronic structure and geometry [4]. This interaction can also be harnessed to create materials and devices with tailored properties, from quantum information systems such as memories [5] and nanophotonic optical isolators [6] to solar cells combining highly absorptive materials with transparent electrodes [7].

The slab geometry is especially appropriate to study light-matter interaction [8, 9]. In the limit of a monolayer, two-dimensional (2D) materials exhibit fascinating optical properties. For simple direct band gap 2D semi-conductors, the single particle band structure implies that the transmission coefficient takes a universal value [10, 11]. This was first measured for single layer graphene samples [12], which have an optical transmission independent of the light frequency in the eV range, \( T = 1 - \sigma \alpha \) where \( \alpha \) is the fine structure constant [13, 14]. The same value was recovered in InAs semiconductors [15]. This universality does not hold for more complex 2D materials, for instance when the Coulomb interaction plays a more important role [16].

Atomic gases represent in many respects an ideal test bed for investigating light-matter interaction. First, they can be arranged in regular arrays [17, 18] or randomly placed [1] to tailor the optical properties of the system. Second, an atom does not absorb light but strongly scatters it with a cross section \( \sigma_0 = 6\pi k^{-2} \) at the optical resonance, where \( k \) is the light wavenumber. Even for thin and much more dilute samples than solid-state systems, strong attenuation of the transmission can be observed at resonance. Third, inhomogeneous Doppler broadening can be made negligible using ultracold atomic clouds. Finally, the geometry and the density of the gases can be varied over a broad range.

In the dilute limit of three-dimensional (3D) atom densities \( \rho \) such that \( \rho k^{-3} \ll 1 \) and for low optical depths, a photon entering the atomic medium does not recurrently interact with the same atom. Then, the transmission from a resonant probe beam propagating along the \( z \) axis reads \( T = e^{-\rho \sigma_0} \) according to the Beer-Lambert absorption law [20]. At larger densities the transmission is strongly modified by the light-induced dipole-dipole coupling between neighboring atoms. The resulting complex correlations between atoms lead to qualitatively new optical response properties, as recently observed in atomic vapors of various geometries: modification of the atomic resonance lineshape [21–31] or super- and sub-radiance [32–36].

In this Letter, we study the transmission of nearly resonant light through uniform slabs of atoms. For dense clouds, we observe a strong increase of the transmission compared to the one expected from the single-atom response. We also measure a broadening and a blue shift of the resonance line on the order of the natural linewidth. This blue shift contrasts with recent measurements on 3D-like cold atomic gases, where red shifts were observed [28, 30, 35]. In addition, we observe deviations of the resonance lineshape from the single-atom Lorentzian behavior, especially in the wings where the transmission decays more slowly. We explore the crossover between dilute clouds and the dense situation by varying independently the atom number and the thickness of this system. We take into account light-induced dipole-dipole interactions between atoms with a “coupled dipole” simulation [1, 37] and compare it, in its regime of validity, with the experimental results.

We start with a brief introduction to our coupled dipole
simulation (for more details, see [38]). We consider the light-atom interaction in an ensemble of \( N \) fixed atoms probed on a \( J = 0 \) to \( J' = 1 \) transition and in the weak saturation limit. In this approach, we compute the exact electric field radiated by this set of dipoles whose values are obtained by solving a system of \( 3N \) linear equations. For dense samples, the eigenmodes associated with this system have a distribution of resonance frequencies and decay rates that are modified compared to the single atom resonance. This method goes beyond the mean-field approximation and takes into account multiple scattering effects to all orders. It is limited by the number \( N \) of atoms that can be simulated with a standard computer, typically up to a few thousands. This in turn restricts the size of the simulated samples to values much smaller than the “macroscopic” experimental cloud. Therefore, coupled dipole simulations are not reliable for optically dense slabs with non-zero thickness, for which the aspect ratio of the simulated clouds is far from the experimental situations [38].

We prepare a cloud of \(^{87}\text{Rb} \) atoms with typically \( N = 1.3(2) \times 10^5 \) atoms in the \( |F = 1, m_F = -1 \rangle \) state. The atoms are confined in an all-optical trap, described in details in [39], with a strong harmonic confinement in the vertical direction \( z \) with frequency \( \omega_z/2\pi = 2.3(2) \) kHz. The transverse confinement along the \( x^- \) and \( y^- \) directions is produced by a flat-bottom disk-shaped potential of diameter \( 2R = 40 \) \( \mu \)m. For our initial cloud temperature \( \simeq 300 \) nK, there is no extended phase coherence in the cloud [2]. Taking into account this finite temperature, we compute for an ideal Bose gas an r.m.s. thickness \( \Delta z = 0.25(1) \) \( \mu \)m, or equivalently \( k\Delta z = 2.0(1) \). This situation corresponds to \( nk^{-2} \approx 1.5 \), where \( n = N/(\pi R^2) \) is the surface density and to a maximum density \( pk^{-3} \approx 0.3 \) at the trap center along \( z \) where \( p \) is the volume density. We tune the number of atoms that interact with light by partially transferring them to the \( |F = 2, m_F = -2 \rangle \) state using a resonant microwave transition. Atoms in this state are sensitive to the probe excitation, contrary to the ones in the \( |F = 1, m_F = -1 \rangle \) state. The cloud thickness can be varied in a controlled way while keeping the atom number constant either by decreasing the strength of the confinement along the vertical direction or by letting the atoms expand for a short time [38]. For the densest clouds, the thickness is also influenced by the measurement itself; indeed, the light-induced dipole-dipole forces between atoms lead to an increase of the size of the cloud during the probing. In the densest case, we estimated from measuring the velocity distribution after excitation that the thickness averaged over the pulse duration is increased by \( \sim 20 \% \).

We probe the response of the cloud by measuring the transmission of a laser beam propagating along the \( z^- \)direction. The light is linearly polarized along the \( x^- \)axis and tuned close to the \( |F = 2 \rangle \rightarrow |F' = 3 \rangle \) \( D_2 \) transition. The duration of the light pulse is fixed to \( 10\) \( \mu \)s for most experiments, and its intensity is below \( 0.2I_{\text{sat}} \), where \( I_{\text{sat}} \approx 1.67 \) mW/cm\(^2\) is the resonant saturation intensity. We define \( \Delta \nu \) as the detuning of the laser beam with respect to the single-atom resonance. The cloud transmission \( T \) is extracted by comparing images with and without atoms and we compute the optical depth \( D = -\ln T \). The numerical aperture of the optical system is limited on purpose to avoid collecting fluorescence light from directions different from the propagation direction of the light beam. With our imaging parameters we can reliably measure optical depths up to 4.

In a first experiment we scan the detuning \( \Delta \nu \) close to resonance and measure the optical depth at a fixed density. The position of the single-atom resonance is independently calibrated using a dilute cloud. The precision on this calibration is of \( 0.03G_0 \), where \( G_0/2\pi = 6.1 \) MHz is the atomic linewidth. The measured resonance curves are fitted with a Lorentzian function:

\[
\Delta \nu \mapsto D_{\text{max}}/[1 + 4(\Delta \nu - \nu_0)^2/G^2].
\]

This function captures well the central shape of the curve for thin gases, as seen in the examples of Fig. 2(a). When increasing the atomic density we observe a broadening of the line \( \Gamma > G_0 \), a non-linear increase of the maximal optical depth \( D_{\text{max}} \) and a blue shift \( \nu_0 > 0 \).

More quantitatively, we show the fitted \( D_{\text{max}} \) for different 2D densities in Fig. 2(b). We compare these results to the Beer-Lambert prediction (narrow dashes) \( D_{BL} = n\sigma_0 \) and to the same prediction corrected by a factor \( 7/15 \).

![FIG. 1. (a) Schematic representation of the imaging setup. The atoms are confined by a single, disk-shaped potential which is imaged using a microscope objective onto a back-illuminated CCD camera. To avoid recollecting fluorescence light, the numerical aperture of the system is limited to \( \sim 0.2 \) using an iris in the Fourier plane of the atoms. (b) Typical in-situ image obtained on a back illuminated CCD camera of the in-plane density distribution averaged over three individual measurements. For this example, the atom surface density is \( n = 25 \) \( \mu \)m\(^{-2}\). We extract a region of interest with uniform density for our analysis.](image-url)
Dipole interactions are of paramount importance in our system. We also show the prediction of the coupled dipole model, as a solid line for the full range of 2D densities at \(k\Delta z = 0\) and as a dotted line for the numerically accessible range of 2D densities at \(k\Delta z = 2.4\). The coupled dipole simulation at \(k\Delta z = 0\) shows a behavior similar to the experiment with \(D_{\text{max}}\) now bounded by 2. One reason for the increase of the experimental bound with respect to the calculation may be the more complex atomic level structure of the experimental configuration. Another reason could be the non-zero thickness of the atomic slab. In order to test this hypothesis, we investigated the influence of probing duration for the largest density. For such a density we could decrease the pulse duration while keeping a good enough signal to noise ratio (see inset in Fig. 2(b)). For shorter probing durations, hence for smaller expansion of the cloud, \(D_{\text{max}}\) decreases, in qualitative agreement with the expected effect of the finite thickness.

We show in Fig. 3(a) the evolution of \(\nu_0\) with density. A blue shift, reaching 0.2\(\Gamma_0\) for the largest density, is observed. At the largest density, an even larger shift is observed when decreasing the pulse duration (see [38]). We also display the result of the coupled dipole model for the cases \(k\Delta z = 2.4\) and \(k\Delta z = 0\). Both simulations confirm the blue shift but predict a different behavior
and a larger effect. In addition, we show the variation of $\nu_0$ for a thick cloud with $k\Delta z = 30(8)$. In that case we observe a marginally significant red shift [42].

The experimental observation of a blue shift has never been reported experimentally to our knowledge. It is in stark contrast, both in amplitude and in sign, with the mean-field prediction of the Lorentz-Lorenz red shift $\nu_0^{MF} = -\sqrt{2\pi nk^{-3}/\Delta z}$. The failure of the Lorentz-Lorenz prediction for cold atoms systems has already been observed and discussed in Refs [28, 43] with different geometries and probing techniques. In these studies, a small red shift was observed. These various behaviors may be explained by inhomogeneous broadening induced by the finite temperature in Ref. [28] and by the specific geometry in Ref. [43], where the size of the atomic cloud is comparable to $\lambda$.

We display in Fig. 3(b) the width $\Gamma$ of the Lorentzian fits for $k\Delta z = 2.4(6)$ along with coupled dipole simulation results [42]. We observe a broadening of the resonance line up to more than $3\Gamma_0$. This broadening is confirmed by the simulation results for $k\Delta z = 0$, but we consider the exact agreement with the experimental data to be coincidental. The range on which we can compute the broadening for $k\Delta z = 2.4$ is too small to discuss a possible agreement.

Finally, we compare the lineshape of the resonance with the Lorentzian shape expected for a single atom. We measure, for $nk^{-2} = 1.5(2)$, the optical depth at large detunings, and for various cloud thicknesses. We fit it with a power law on the red-detuned (resp. blue-detuned) frequency interval with exponent $\eta_r$ (resp. $\eta_b$) as shown, for two examples, in the inset of Fig. 4. If the behavior were indeed Lorentzian, the exponents should be $-2$ in the limit of large detuning. As seen in Fig. 4, for the thinnest gases, the fitted exponents are significantly different from the expected value and can reach values up to $-1.3$, showing the strong influence of dipole-dipole interactions in our system. Our experimental results interpolate between the single atom case and the simulated 2D situation where we compute the exponents $\eta_r = -0.36(1)$ and $\eta_b = -0.70(1)$.

In summary we have studied the transmission of a macroscopic dense cloud of atoms and showed a spectacular reduction of the maximum optical density, a broadening and a large blue shift of the resonance line. We reproduce qualitatively these behaviors with coupled dipole simulations. The observed differences may be attributed to the complex atomic level structure of the atoms that is not considered in the simulations or because of residual motion of the atoms induced by the strong dipole-dipole interactions. The discussion about light transmission in 2D solid-state systems is thus expanded to a new regime by this work. Finally, we note that this Letter is focused on the steady-state transmission of a cloud illuminated by a uniform monochromatic beam. It would be interesting to extend this study to time-resolved experiments, to fluorescence measurements or to spatially resolved propagation of light studies.

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[2] The 2D phase-space density of the cloud is below the transverse condensation threshold as defined in [44].

[41] The observed saturation is not due to our detection procedure. In the fitting procedure, we only select points with a measured optical depth below 3 to avoid any bias.

[42] For thick clouds the expected optical depth of the cloud becomes larger than the maximal value we can detect. We then only fit the points with a measured optical depth below 3. From this fit we cannot estimate reliably the value of the maximum and width of the resonance line, but we can get an estimate of the “center” of the line which may deviate from the position of the maximum of the resonance for an asymmetric lineshape.

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SUPPLEMENTAL MATERIAL FOR:
TRANSMISSION OF NEAR-RESONANT LIGHT
THROUGH A DENSE SLAB OF COLD ATOMS

A - EXPERIMENTAL METHODS

A1 - Atom number calibration

As demonstrated in the Letter, dipole-dipole interactions strongly modify the response of the atomic cloud to resonant light and make an atom number calibration difficult. In this work, we measure the atom number with absorption imaging for different amounts of atoms transferred from the $F = 1$, $m_F = -1$ “dark” state to the $F = 2$, $m_F = -2$ state in which the atoms are resonant with the linearly polarized probe light. We perform resonant Rabi oscillations for this coherent transfer and fit the measured atom number as a function of time by a sinus square function. We select points with an OD below 1, to limit the influence of dipole-dipole interactions, and corresponding to either a weak excitation or to an excitation around a $2\pi$ pulse, to make the fit more robust. From the measured optical depth $D$, we extract $n k^{-2} = (15/7) D/(6\pi)$. The factor $7/15$ corresponds to the average of the squared Clebsch-Gordan coefficients for linearly polarized light resonant with the $F = 2$ to $F' = 3$ transition. This model does not take into account possible optical pumping effects that could lead to a systematic error on the determination of the atom number.

A2 - Computation of the optical depth

We extract the optical depth ($D$) of the clouds by comparing pictures with and without atoms. The read-out noise on the count number $N_{\text{count}}$ is $dN_{\text{count}} \sim 5$ per pixel. We subtract from these images equivalent pictures without any imaging pulse to remove the background counts and obtain two pictures $M_{\text{with}}$ and $M_{\text{without}}$. The typical noise on the count number per pixel is thus $dN = \sqrt{2}dN_{\text{count}} \sim 7$.

The magnification of the optical system is 11.25, leading to an effective pixel size in the plane of the atoms of 1.16 $\mu$m. We limit the imaging intensity $I$ to the weakly saturating regime with $0.075 < I/I_{\text{sat}} < 0.2$ ($I_{\text{sat}} = 1.6 \text{ mW/cm}^2$). The mean number of counts per pixel accumulated during the 10$\mu$s imaging pulse is 80 on the picture without atoms. We optimize the signal-to-noise ratio by summing, for $M_{\text{with}}$ and $M_{\text{without}}$, all the pixels in the region of interest. This yields a total count number in the picture with atoms $N_{\text{with}}$ and without atoms $N_{\text{without}}$ from which we compute the optical depth: $D = -\ln(N_{\text{with}}/N_{\text{without}})$. The region of interest varies with the time-of-flight of the cloud. This region is a disk that ensures that we consider a part of the cloud with constant density, comprising typically 200 pixels. At low densities, the error on $D$ due to the read-out noise is about 0.01. At $D \sim 3$, i.e. the maximum value that we consider to fit the data, it reaches 0.12.

A3 - Variation of the cloud thickness

The spatial extent of the cloud can be controlled using mainly two techniques: (i) Varying the vertical harmonic confinement by modifying the laser power in the blue-detuned lattice that traps the atoms, thus changing its frequency from $\omega_z/2\pi = 1.1(2)$ kHz to $\omega_z/2\pi = 2.3(2)$ kHz. Using the ideal Bose gas statistics in the tight harmonic trap, for a gas of $N = 1.3(2) \times 10^5$ atoms at a temperature of $T \simeq 300 \text{ nK}$, this corresponds to thicknesses between 0.3 $\mu$m and 0.6 $\mu$m. (ii) Allowing the atoms to expand for a short time after all traps have been switched off. The extent of the gas in the $xy$-direction does not vary significantly during the time of flight (ToF) (duration between 0.7 ms and 4.7 ms). In that case, the thickness varies between 3 $\mu$m and 25 $\mu$m.

Additionally, the thickness of the cloud is modified during the probe duration by light-induced dipole-dipole interactions. We estimate that this leads to an averaged thickness of the densest clouds which is 1.2 times larger than the one computed from the ideal Bose gas statistics. We can limit this effect by reducing the probe duration $\tau$ down to 3 $\mu$s.

A4 - Fitting procedures

A4.1 - Lorentzian fit

We fit the raw optical depth data points as a function of detuning $\Delta \nu$ (with typically three repetitions by frequency) with a Lorentzian function:

$$\Delta \nu \rightarrow D(\Delta \nu) = D_{\text{max}}/[1 + 4(\Delta \nu - \nu_0)^2/T^2].$$

The origin of frequencies is determined by taking a resonance curve for a dilute gas, and we restrict the fitting domain to $|\Delta \nu| < 30$ MHz. All points with values of $D$ above 3 are discarded to avoid potential systematic errors. For thick gases, that is for large time-of-flights, this typically removes the measurements at detunings smaller than 10 MHz. Hence, in this case, we consider the amplitude and the width of the fits to be not reliable enough and use the center of the resonance $\nu_0$ with caution.

The errors on the fitted parameters are determined using a basic bootstrap analysis, repeating the fitting procedure 100 times on a set of random points drawn from the original set of data, of the same length as this original set.
Here we consider the raw optical depths at large detunings. Our experimental setup allows to explore detunings with respect to the dilute cloud resonance between -95 MHz and +35 MHz. We restrict ourselves to $|\Delta \nu| \in [10, 33]$ MHz and to optical densities such that $\Delta > 0.009$. We perform two power-law fits, one on the red-detuned and one on the blue-detuned side of the resonance, to extract the exponents $\eta_h$ and $\eta_b$ using the function:

$$\Delta \nu \rightarrow D(\Delta \nu) = A (\Delta \nu - \nu_0)^\eta,$$

with $\nu_0$ the fitted center of the resonance according to the lorentzian fit. We consider that the fit is reliable as soon as we have more than 16 data points for a given thickness, atom number and side of the resonance.

The error on the fitted exponents is also determined using a bootstrap analysis.

### B - COUPLED DIPOLE SIMULATIONS

Our approach to simulate the experiments with the coupled dipole model follows the description in Ref. [S1]. We consider atoms with a $J = 0 \rightarrow J = 1$ transition. For a given 2D density $n$ and thickness $\Delta z$ we draw the positions of the $N$ atoms with a uniform distribution in the $xy$ plane and a Gaussian distribution along the $z$ direction. The number of atoms and hence the disk radius is varied to perform finite-size scaling. For a given detuning and a linear polarization along $x$ of the incoming field, we compute the steady-state value of each dipole $\mathbf{d}_j$ which is induced by the sum of the contributions from the laser field and from all the other dipoles in the system. The second contribution is obtained thanks to the tensor Green function $g_{\alpha\beta}$ giving the field radiated at position $\mathbf{r}$ by a dipole located at origin:

$$g_{\alpha\beta}(\mathbf{r}) = \frac{k^3}{4\pi\varepsilon_0} \frac{e^{ikr}}{kr} \left[ \left( 1 + \frac{i}{kr} - \frac{1}{(kr)^2} \right) \delta_{\alpha\beta} - \left( 1 + \frac{3i}{kr} - \frac{3}{(kr)^2} \frac{r_\alpha r_\beta}{r^2} \right) \right].$$

Practically, the values of the $N$ dipoles are obtained by exactly solving a set of $3N$ linear equations, which limits the range of atom number to a few thousands, a much lower value than in the experiment (where we have up to $10^5$ atoms). From the values of the dipoles we obtain the transmission $T$ of the sample:

$$T = 1 - \frac{i}{2} \sigma \frac{nk^2}{N} \sum_j \frac{k^3}{6\pi\varepsilon_0 E_L} d_{j,x} e^{-ikz_j}$$

where $z_j$ is the vertical coordinate of the $j$-th atom, $E_L$ the incoming electric field, and $d_{j,x}$ is the $x$ component of the dipole of the $j$-th atom.

We show two examples of the finite-size scaling approach for $k\Delta z = 1.6$ in Fig.1 and $k\Delta z = 80$ in Fig.2. For low enough densities, the results of the simulations (maximal optical depth, width, shift,...) for different atom numbers in the simulation are aligned, when plotted as a function of $1/\sqrt{N_{\text{sim}}}$ and allow a finite-size scaling approach. All the results presented in the main article [?] are obtained by taking the extrapolation to an infinite system size, which corresponds to the offset of the linear fit in the figure.

**FIG. 1.** Example of finite-size scaling to determine the position of the maximum of the resonance $\nu_0$. Here $k\Delta z = 1.6$ and (from bottom to top) $nk^{-2} = 0.05, 0.11, 0.16$ and $0.21$. Simulations are repeated for different atom number $N_{\text{sim}}$. The number of averages ranges from 75 (left points, $N_{\text{sim}} = 2000$) to 25000 (right points, $N_{\text{sim}} = 100$). When plotting the shift as a function of $1/\sqrt{N_{\text{sim}}} \propto R$, and for low enough densities, data points are aligned and allow for a finite-size scaling. Vertical error bars represent statistical uncertainty obtained when averaging the results over many random atomic distributions.

Interestingly, we observe in Fig.1 that considering a finite-size system only leads to a small underestimate of the blue shift of the resonance. However, for thicker systems, such as in Fig. 2, we get, for finite systems, a small red shift and a narrowing of the line. Considering our experimental system, we have $1/\sqrt{N} \approx 0.003$, leading to a small correction according to the fits in Fig. 2. However, we are able to simulate only systems with low $nk^{-2}$, typically 0.1, whereas we can reach densities 15 times larger in the experiment, which could enhance finite-size effects.

### C - COMPLEMENTARY RESULTS

**C1 - Influence of the light pulse duration**

The inset in Fig. 2(b) in the main text shows the influence of the light pulse duration on the measured maximal optical depth for the thin and dense configuration. We show in Fig. 3 the value of the width and the position of the maximum of the resonance line extracted from this fit. The width of the resonance line is not influenced much by the pulse duration but the shift gets larger for
shorter pulse durations. This trend is consistent with the increase of the blue shift when decreasing the cloud thickness observed with coupled dipole simulations (see Sec. C3).

\[ k\Delta_z = 80 \text{ and (from top to bottom)} \]
\[ \eta k^{-2} = 0.027, 0.080 \text{ and } 0.13. \]

Simulations are repeated for different atom number \( N_{\text{sim}} \). The number of averages ranges from 75 (left points, \( N_{\text{sim}} = 2000 \)) to 25 000 (right points, \( N_{\text{sim}} = 100 \)). Vertical error bars represent statistical uncertainty obtained when averaging the result over many random atomic distributions.

We display in Fig. 4(b) in the main text power-law exponents extracted from data computed with the coupled dipole simulation at \( \Delta z = 0 \). We use the same fitting procedure as for the experimental data to get the exponents. We report in Fig. 4 the evolution of the optical depth with detuning for both sides of the resonance along with the power-law fit \( A\Delta^{\eta} \). For the red side, we get \( \eta_r = -0.36(1) \) and for the blue side, we get \( \eta_b = -0.70(1) \).

**C3 - Role of the cloud thickness**

We show in Fig. 5 the influence of the thickness of the cloud calculated using the coupled dipole simulations. We limit the study to low densities, for which the finite-size scaling approach works. It is important to note that the computed line shapes deviate significantly from a Lorentzian shape and become asymmetric. The center of the line and its width are thus not well-defined quantities. In our analysis, we fit the resonance lines around their maximum with a typical range of \( \pm 0.5 \Gamma \). The blue shift thus corresponds to a variation of the position of the maximum of the line and the “width” characterizes the curvature of the line around its maximum. In these plots, we observe that the main features described in the main text, namely the decrease of maximal optical depth and the blue shift, gets more pronounced for small thicknesses and becomes significant for \( k\Delta z < 1 \).

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FIG. 5. Coupled dipole simulations for different thicknesses. (a) Maximal optical depth, (b) Position of the maximum of the line, (c) Width of the resonance line. We report results for $k\Delta z = 0, 1.6, 3.2, 8$ and 40, the darkest lines corresponding to the smallest thicknesses. The black dashed lines correspond to the single-atom response.

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[S1] L. Chomaz, L. Corman, T. Yefsah, R. Desbuquois, and J. Dalibard, New J. Phys. 14, 055001 (2012).

[S2] Except for Fig. 4(b) for which simulations are performed for a fixed atom number of 2000.