Universal approach for quantum interface and memory with atomic arrays

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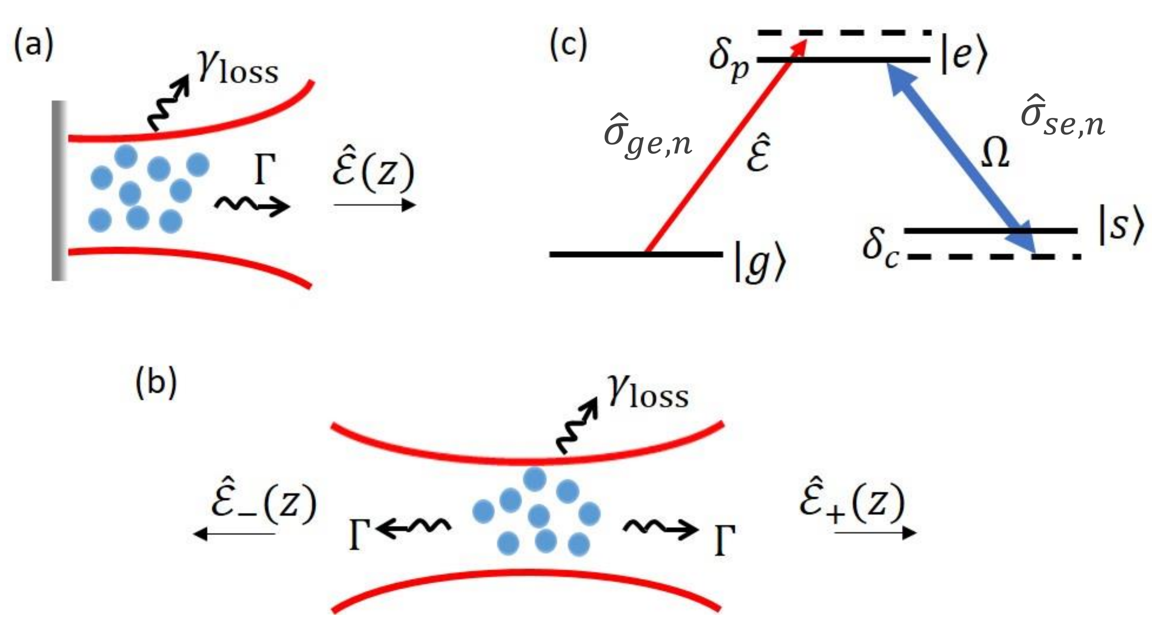
Abstract

We develop a general analytical approach for the characterization of atom-array platforms as light-matter interfaces, focusing on their application as a quantum memory. Our approach is based on the mapping of various atom-array systems into a generic 1D model of light interacting with a collective atomic dipole. We find that, generically, the efficiency of light-matter coupling and quantum memory is given by the on-resonance reflectivity of the 1D scattering problem, $r_0 = C/(1+C)$, where C is a cooperativity parameter of the model. For relevant cases of 2D and 3D arrays in free space, we analytically derive their effective cooperativity parameter, while accounting for realistic effects such as the finite sizes of the array and illuminating beam, non-subwavelength arrays, and weak disorder in atomic positions. Our analytical results are verified numerically and demonstrate that efficiencies of quantum tasks are reduced by our approach to the classical calculation of a reflectivity. Implications on light-matter interfaces realized by optical lattices or tweezer arrays are discussed.

Introduction: General 1D model



Symmetric mode

$$\hat{\mathcal{E}}(z) = \frac{1}{\sqrt{2}}\left(\hat{\mathcal{E}}_-(z)+\hat{\mathcal{E}}_+(z)\right)$$

Dynamical equations

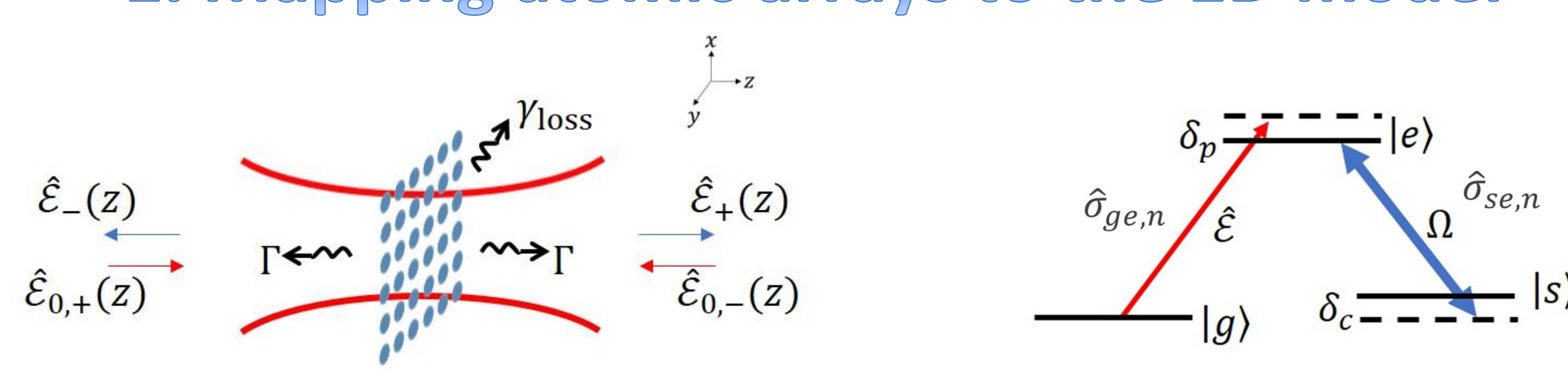
$$\frac{d\hat{P}}{dt} = \left[i(\delta_p-\Delta) - \frac{\Gamma+\gamma_{\rm loss}}{2}\right]\hat{P} + i\Omega\hat{S} + i\sqrt{\Gamma}\hat{\mathcal{E}}_0(0,t) + \hat{F}(t)$$

$$\frac{d\hat{S}}{dt} = i\delta_2\hat{S} + i\Omega^*\hat{P} \qquad \delta_2 = \delta_p - \delta_c$$

$$\hat{\mathcal{E}}(z) = \hat{\mathcal{E}}_0(z) + i\sqrt{\Gamma}\hat{P}$$

Cooperativity: $C = \frac{\Gamma}{\gamma_{\rm loss}}$ → Efficiency: $\frac{C}{1+C}$

1. Mapping atomic arrays to the 1D model



Finite array & finite Gaussian beam

$$u(\mathbf{r}) = \sqrt{\frac{2}{\pi w_0^2}}\, e^{-\frac{\mathbf{r}^2}{w_0^2}}$$

$$\eta = \int_{L^2} |u(\mathbf{r})|^2 d\mathbf{r} = \mathrm{erf}^2\left(\frac{L}{\sqrt{2}w_0}\right)$$

$$\hat{\sigma}_{ge,n} \to \hat{P} = \frac{a}{\eta}\sum_n \hat{\sigma}_{ge,n} u(\mathbf{r}_n)$$

$$\hat{\sigma}_{se,n} \to \hat{S} = \frac{a}{\eta}\sum_n \hat{\sigma}_{se,n} u(\mathbf{r}_n)$$

$$\frac{\Gamma_0}{2} + i\Delta_0$$

Assumptions

$w_0 \gg \lambda$

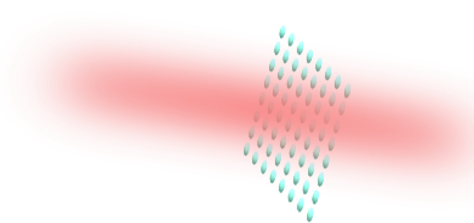
$L \gg \lambda$

$\sqrt{N} \gg 1$

2. Cooperativity & reflectivity

Reflectivity of 2D array:

$$r = -\frac{\Gamma_0}{\Gamma_0 + \gamma_{\rm loss} + 2i(\delta_p - \Delta_0)}$$



Reflectivity at resonance = efficiency:

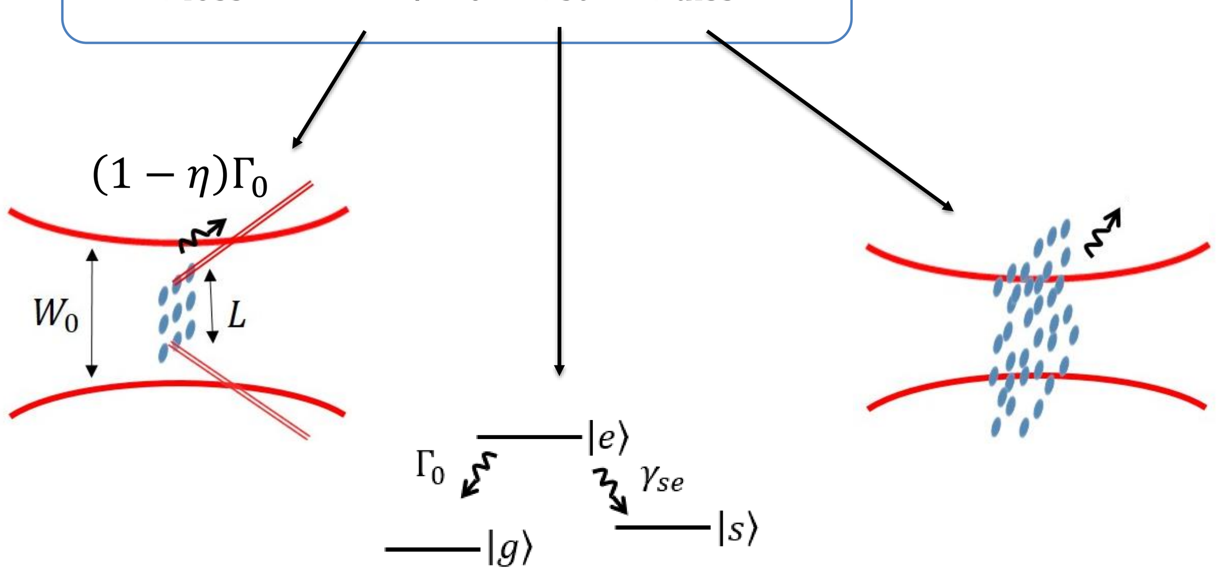
$$\delta_p = \Delta_0 \;\to\; r_0 = \frac{C}{1+C} \qquad C = \frac{\eta\Gamma_0}{\gamma_{\rm loss}}$$

High cooperativity → "Perfect mirror"

E. Shahmoon, et al. PRL 118, 113601 (2017); R. J. Bettles, et al. PRL 116.10 (2016): 103602; J. Rui, et al. Nature 583.7816 (2020): 369-374.

3. Subwavelength array $a<\lambda$

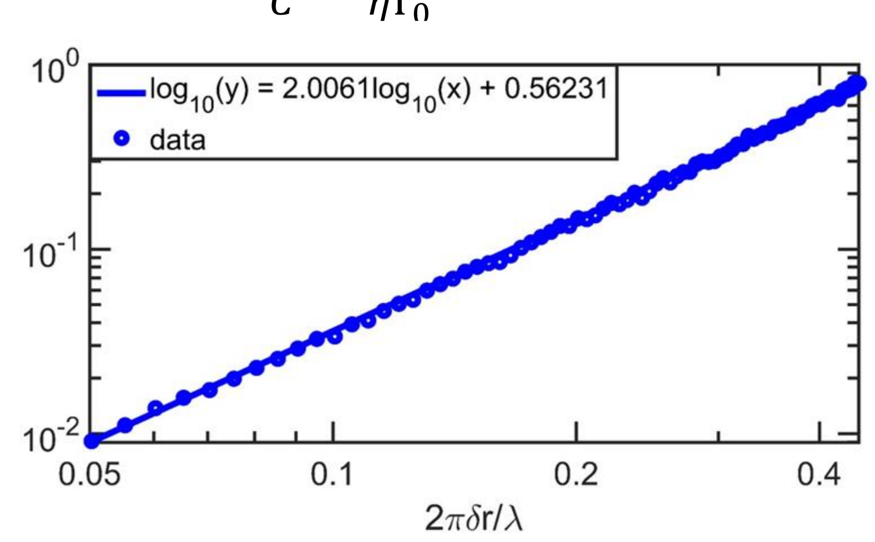
$$\gamma_{\rm loss} = (1-\eta)\Gamma_0 + \gamma_{se} + \gamma_{\rm diss}$$



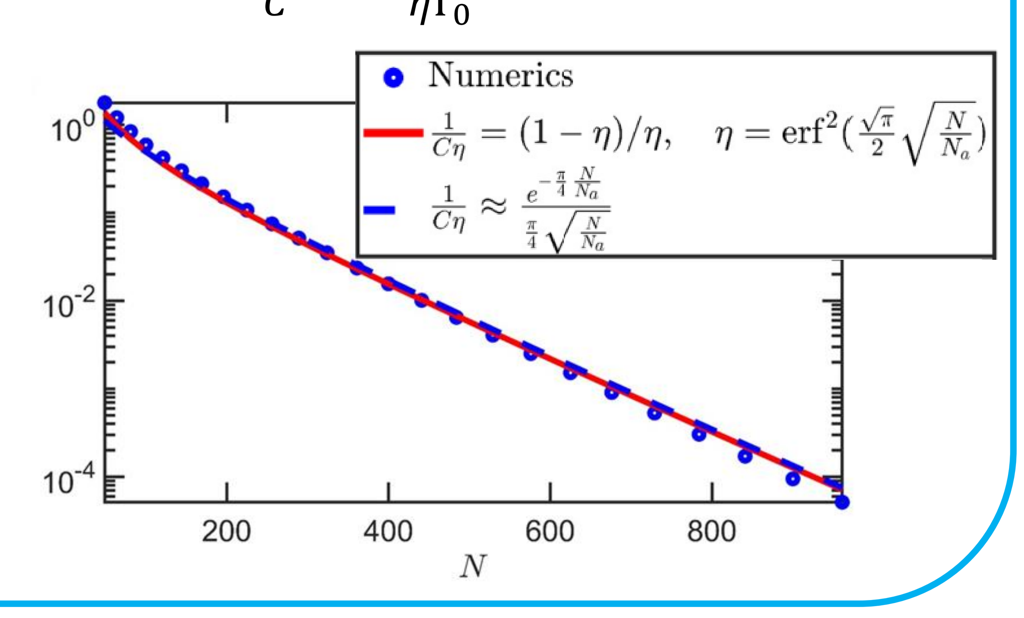
Error scaling

$$C = \frac{\eta\Gamma_0}{\gamma_{\rm loss}}$$

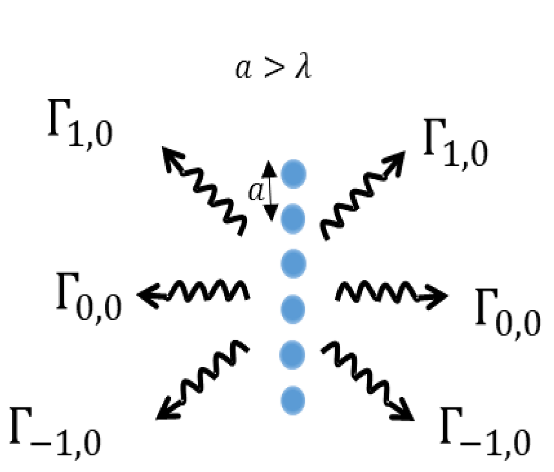
$$\frac{1}{C} = \frac{\gamma_{\rm diss}}{\eta\Gamma_0} \;(\eta\to 1)$$

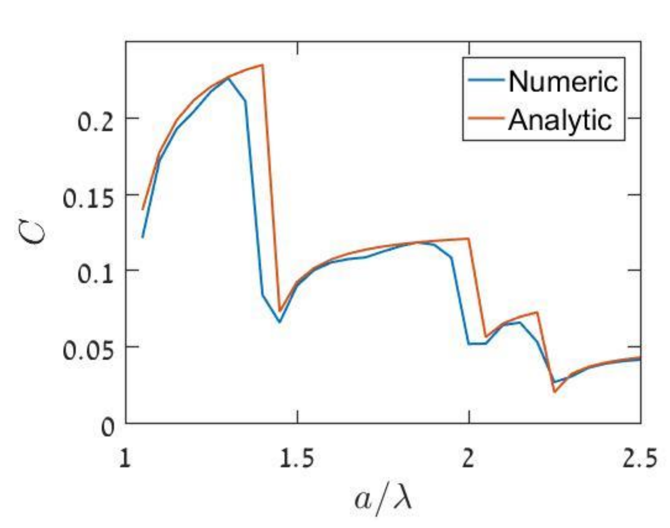


$$\frac{1}{C} = \frac{(1-\eta)\Gamma_0}{\eta\Gamma_0} \;(\gamma_{\rm diss}\to 0)$$



4. Super-wavelength array $a>\lambda$



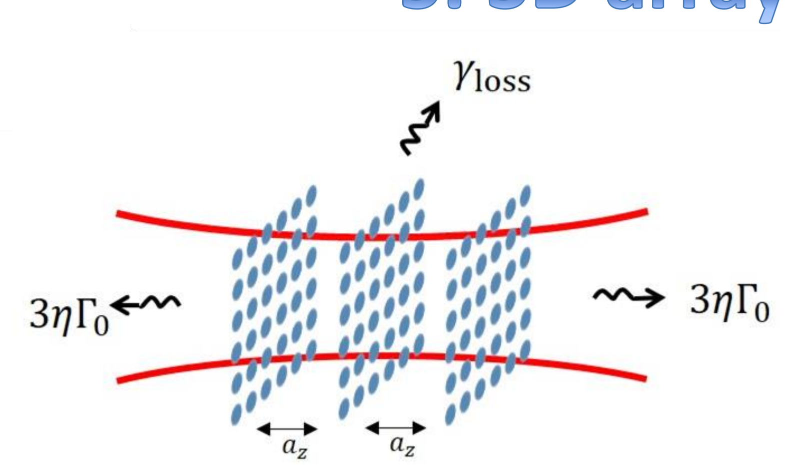


$$\gamma_{\rm diff} = \sum_{\substack{|(m_x,m_y)|<\frac{a}{\lambda}\\ (m_x,m_y)\neq(0,0)}} \Gamma_{m_x,m_y}$$

$$\Gamma_{m_x,m_y} = \frac{\Gamma_0}{q}\frac{q^2 - |\mathbf{q}_{m_x,m_y}\cdot\mathbf{e}_d|^2}{\sqrt{q^2 - |\mathbf{q}_{m_x,m_y}|^2}}$$

$$\mathbf{q}_{m_x,m_y} = \frac{2\pi}{a}(m_x, m_y)$$

5. 3D arrays



$$e^{i\omega_p/c|z-a_z n_z|}$$

$$\hat{P} = \frac{a}{\eta}\sum_n\sum_{n_z}\hat{\sigma}_{ge,n,n_z}u(\mathbf{r}_n)$$

Phase matching:

$$a_z = n\lambda$$

$$\Gamma_0 \to N_z\Gamma_0 \qquad C \to \frac{\eta N_z\Gamma_0}{\gamma_{\rm loss}}$$

Prospects

- Super-wavelength array placed in a cavity which will reduce the losses of higher diffraction orders.
- Nonlinear atom array: utilizing the strong atom-photon coupling with the array to produce entangled states of light.