Quantum nonlinear optics based on 2D Rydberg atom arrays

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In this project [1], we explore the combination of sub-wavelength, two-dimensional atomic arrays, and Rydberg physics as a powerful platform to realize strong, coherent interactions between individual photons with high fidelity. In particular, the spatial ordering of the atoms guarantees efficient atom-light interactions without the possibility of scattering light into unwanted directions, for example, allowing the array to act as a perfect mirror for individual photons (Fig. 1a). In turn, Rydberg interactions enable single photons to alter the optical response of the array within a potentially large blockade radius R_b, which can effectively punch a large "hole" for subsequent photons (Fig. 1b). Such a system enables a coherent photon-photon gate or switch, with an error scaling that is significantly better than the best-known scaling in a disordered ensemble (Fig. 1c,d).

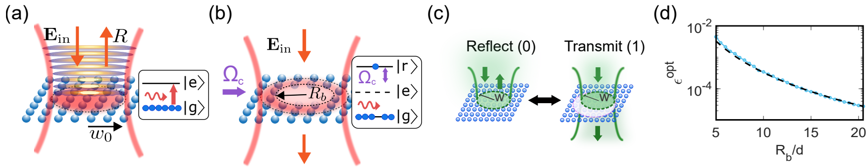

FIG. 1. (a) Illustration of a sub-wavelength 2D array of two-level atoms ($|g\rangle$, $|e\rangle$) reflecting a resonant input gaussian beam with beam waist w_0. (b) Next, we consider a Rydberg state $|r\rangle$ coupled to the $|e\rangle$ levels by means of a control field Ω_c. Storing a Rydberg excitation results in an energy shift that breaks the mirror resonance condition within the *blockaded region* of radius R_b. (c) Combining the phenomena from (a-b) we build a single-photon switch, where the transmission/reflection of a signal photon is conditioned to the storage/retrieval of a gate photon. (d) Switch error ϵ (photon loss) as a function of R_b after optimizing the system's parameters. Scaling ($\epsilon^{opt} \sim R_b^{-4}$) and predicted values outperform current ensemble-based protocols.

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[1] M. Moreno-Cardoner, D. Goncalves, and D. E. Chang,(2021), arXiv:2101.01936 [quant-ph].

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