Directional quantum scattering transducer in cooperative Rydberg metasurfaces

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We present a single-photon transduction scheme using 4-wave-mixing and quantum scattering in planar, cooperative Rydberg arrays that is both efficient and highly directional and may allow for terahertz-to-optical transduction. In the 4-wave-mixing scheme, two lasers drive the system, coherently trapping the system in a dark ground-state and coupling a signal transition, that may be in the terahertz, to an idler transition that may be in the optical. The photon-mediated dipole-dipole interactions between emitters generate collective super-/subradiant dipolar modes, both on the signal and the idler transition. As the array is cooperative with respect to the signal transition, an incident signal photon can efficiently couple into the array and is admixed into dipolar idler modes by the drive. Under specific criticality conditions, this admixture is into a superradiant idler mode which primarily decays into a specific, highly directional optical photon that propagates within the array plane. Outside of the array, this photon may then be coupled into existing quantum devices for further processing. Using a scattering-operator formalism we derive resonance and criticality conditions that govern this two-step process and obtain analytic transduction efficiencies. For infinite lattices, we predict transduction efficiencies into specific spatial directions of up to 50%, while the overall, undirected transduction efficiency can be higher. An analysis for finite arrays of N^2 emitters, shows that the output is collimated into lobes that narrow as $1/\sqrt{N}$. Our scheme combines the broadband acceptance of free-space 4-wave mixing with the efficiency, directionality and tunability of cooperative metasurfaces, offering a route towards quantum-coherent THz detection and processing for astronomical spectroscopy, quantum-networked sparse-aperture imaging and other quantum-sensing applications [1].

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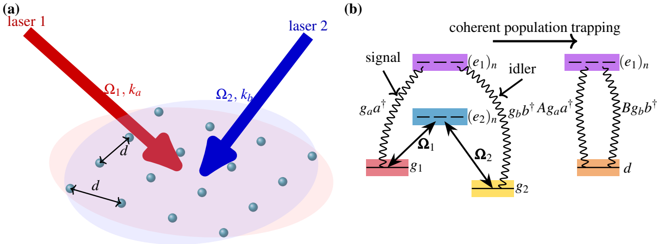

Fig. 1: Schematic view of the experimental setup and level scheme of an individual atom site. (**a**) Rydberg atoms are arranged in a square lattice with spacing d in the x-y plane. The array is illuminated (ellipses) by two driving lasers, laser 1 (red) and laser 2 (blue). (**b**) The level structure of each atom site features a double Λ-system which shares the ground states g_1 and g_2. In the lower Λ-system the lasers 1 and 2 couple the ground states to a manifold of excited states $(e_2)_n$. In the upper Λ-system the ground states couple to another manifold of excited states $(e_1)_n$. The $g_1 \leftrightarrow e_1$ and $g_2 \leftrightarrow e_1$ transitions couple to quantized electromagnetic fields a and b with vacuum coupling strength g_a and g_b. Due to the strong drive on the lower Λ-system, the ground state manifold is coherently trapped in a dark state superposition d of the two ground states, which now couples to the excited state manifold $(e_1)_n$ through the signal field a and the idler field b with effective coupling strengths Ag_a and Bg_b, effectively admixing the associated dipolar surface modes.

References

[1] J. von Milczewski, K. Werker Smith, S. F. Yelin, arXiv:2510.27654 (2025)