Simulating quantum light propagation through atomic ensembles using matrix product states

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Atomic ensembles constitute a powerful and versatile platform to realize a quantum interface between matter and light. Recently, a number of such interfaces have emerged, most prominently ensembles with atoms excited to high-lying Rydberg states, which enable strong nonlinear interactions between propagating photons. A largely open problem, which is difficult to treat both analytically and numerically, is whether these systems can produce exotic quantum many-body states of light, and the development of new techniques to solve for the out-of-equilibrium quantum dynamics as photons propagate and interact with atoms is highly desirable. Here, we describe a novel numerical approach, wherein a problem involving quasi one-dimensional light propagation is mapped to the dynamics of an open 1D interacting "spin" system describing the atomic internal degrees of freedom, where all photon correlations are obtained from those of the spins by a quantum input-output relation. The spin dynamics in turn are numerically solved using the powerful matrix product state ansatz, which avoids the exponentially large Hilbert space nominally associated with the spins. As two specific examples, we apply this formalism to investigate vacuum induced transparency, a phenomena where the different photon number components of a pulse propagate with number-dependent group velocity and separate at the output, and Rydberg EIT in the high-photon limit, where it becomes possible to generate pulse trains of single photons starting from continuous input fields.