Limits of mean-field models for light propagation in material samples: the refractive index of a dense and cold atomic cloud

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When light propagates through dense media, the collective response of scatterers leads to an effective refractive index whose apparent upper bound, close to unity in most materials, remains poorly understood. Recent theoretical work attributes this behavior to cooperative effects such as recurrent scattering and dipole–dipole interactions, but experimental evidence remains limited. Cold atomic systems offer a unique platform to investigate this problem, as they enable precise control over density, geometry, and light–matter interactions. The main goal of this work is therefore to quantify how the refractive index of a cold atomic ensemble depends on matter density and to identify the mechanisms responsible for its saturation. For this, we develop an experimental setup for laser cooling and trapping of Sr^{88} atoms, implement phase-resolved measurements of the transmitted light field, and perform numerical simulations of interacting atomic dipoles. This combined approach allows us to directly probe cooperative effects beyond standard mean-field models. By answering how collective scattering limits the refractive index, and whether these effects can be engineered, this research seeks to deepen our understanding of light transport in complex media and to enable applications ranging from advanced imaging techniques to the design of novel optical materials.

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