PhD THESIS DEFENSE: Multiple light scattering in atomic media: from metasurfaces to the ultimate refractive index

FRANCESCO ANDREOLI

March 23, 2023

11:00

ICFO Auditorium and Online (Teams)

Our ability to confine, guide, and bend light has led to astonishing technological achievements, playing a fundamental role in diverse fields like microscopy, photochemistry, telecommunications or material design. The key property of materials that allows to control light is the refractive index. Notably, regardless of very different microscopic structures, all natural materials exhibit a modest, near-unity index of refraction, n ~ 1. This universality suggests the existence of some simple, ubiquitous origin, whose complete characterization from microscopic considerations, surprisingly, is still missing. Moreover, one can wonder which principles might allow to synthesize a material with an ultra-high index, to boost the

performance of photonic devices.
In this thesis, we address these questions from an atomic-physics standpoint, exploring if the macroscopic optical properties can be related to simple, electrodynamical processes occurring between well-separated atoms, which only interact via light scattering. Standard theories neglect that light can be scattered multiple times, and lead to unphysical predictions when strong interference occurs between the coherent atomic emission, such as in dense atomic ensembles or ordered lattices. We here develop new techniques to address the physics of multiple light scattering, with the ultimate goal of understanding the fundamental limits to the refractive index, as well as proposing unexpected photonic applications. Our results are divided in three parts.
First, we investigate an ensemble of ideal atoms with increasing atomic density, starting from the dilute gas limit, up to dense regimes where a non-perturbative treatment of multiple scattering and near-field interactions is required. In this situation, we find that these effects limit the index to a maximum value of $n \sim 1.7$, in contrast with standard theories. We propose an explanation based upon strong-disorder renormalization group theory, in which the near-field interactions combined with random atomic positions result in an inhomogeneous broadening of the atomic resonance frequencies. This basic mechanism ensures that regardless of the physical atomic density, light at any given frequency only interacts with at most a few near-resonant atoms per cubic wavelength, thus limiting the index attainable.
Afterwards, we show that a radically different behavior is expected for an ideal, atomic crystal. As long as the inter-atomic interactions are only mediated by multiple scattering, each 2D array of the crystal exhibits a lossless, single-mode response, which builds up a very large and purely real refractive index. To address the limits to this picture, we extend our theoretical analysis to much higher densities, where the electronic orbitals on neighboring nuclei begin to overlap. We develop a minimal model to include the onset of this regime into our non-perturbative analysis of multiple light scattering, arguing that the emergence of quantum magnetism, density-density correlations and tunneling dynamics of the electrons effectively suppresses the single-mode response, decreasing the index back to unity. Nonetheless, right before the onset of chemistry, our theory predicts that an ultra-high-index ($n \sim 30$) and low-loss material could in principle be allowed by the laws of nature.
Finally, inspired by the impressive optical response of atomic arrays, we propose their use as a more complex optical device, namely a thin lens. The building blocks of this "atomic metalens" are composed of three consecutive 2D arrays, whose distance and lattice constants are suitably chosen to guarantee a high transmission of light, as well as an arbitrary phase shift. To characterize its efficiency and prove its robustness against losses, we perform large-scale numerical simulations, on a number of atoms between one and two orders of magnitude larger than comparable works.

Hosted by: Prof. Dr. Darrick Chang