Project title: Quantum thermodynamics in randomized structures

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Current state of the art

In the past decade, many efforts have been devoted to understand how, starting from an isolated quantum system evolving under Hamiltonian dynamics, equilibration and effective thermodynamics emerge at long times[1]. On the other hand, the investigations of open quantum systems have sparked interest on the issue of quantum thermodynamics taking place under the quantum evolution of open systems [2]. The questions of how thermodynamics emerges from quantum dynamics, how quantum systems dynamically equilibrate and thermalize, and whether thermalization is always reachable in the quantum regime, are at the core of quantum thermodynamics research. Evidently, a fundamental ingredient of the physics of thermodynamics is statistics, that is, the random nature of the system under investigation. Our team is among the pioneers of implementing random walks of quantum light in randomized photonic structures [3], using integrated quantum waveguide circuits fabricated with the laser direct-write approach [4]. When ultrashort laser pulses are tightly focused into transparent bulk material, nonlinear absorption takes place leading to optical breakdown and the formation of a micro plasma, which induces a permanent change in the material's molecular structure. In the particular case of fused silica as host material, the density is locally increased, yielding a permanent increase of the refractive index. The dimensions of these changes are approximately the same as the size of the focal region. By moving the sample transversely with respect to the beam a continuous modification is obtained and a waveguide is created (see Fig. 1a). Such guides can be written in almost any arrangements along arbitrary paths, since the only limiting factor in the placement of the focus is the focal length of the writing objective. In our work on randomized photonic waveguide structures, we fabricated extended lattices of waveguides with randomized spacing [5] and randomized refractive indices [6], resulting in statistical propagation dynamics of the entire wave function (see Fig. 1b). When launching quantum light into these structures and examining the two-particle correlation functions, one observes that besides the expected bosonic bunching of the photons a thermalization process occurs due to which the photons localize in the center of the structure (see Fig. 1c), apparently undergoing a transition from ballistic transport to localization.

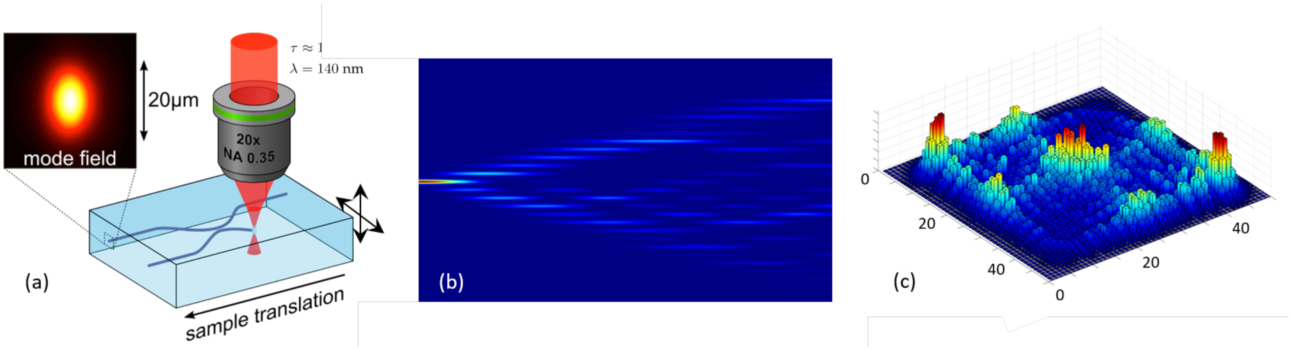

Figure 1: (a) Setup for writing waveguides using ultrashort laser pulses. The inset shows a typical waveguide mode. (b) When the waveguides are randomized in their spacing or their refractive index, the light evolution becomes statistical. (c) When launching two indistinguishable photons into such a structure results in a partially thermalized two-particle correlation function: Besides the typical bosonic bunching of the photons, they also show signatures of localization in the center of the structure, as the ballistic transport is suppressed.

Research goals and working program

Quantum thermodynamics - despite being a mature field of theoretical research - is still in its infancy in terms of experiments [7]. While it is generally agreed that this field does not only provide deep insights into the very connection of statistics and thermodynamic, it does also holds great promise for technological applications. Along these lines, this PhD project aims to **explore the impact of thermalization of photonic quantum states in integrated randomized structures.**

Based on our experience in fabricating extended randomized waveguide circuits for the exploration of, e.g., Anderson-localization [5] and disordered topological transport [6], we will explore the impact of coupling the system to an external thermal reservoir such that energy can be exchanged (see Fig 2a). In the photonic context, these can be represented by different types of waveguide lattices: Ordered waveguide arrangements standing in for the system under consideration, and ones with randomized waveguide spacings/refrative indices representing the reservoir at a temperature $T > 0$ (see Fig. 2b). With such a platform at hand, various non-classical phenomena of propagating single-photon states can be investigated. As an example, consider a three-photon entangled state in its ground state. During its propagation, one of the photons might be coupled into the reservoir and effectively isolated. The rest of the state, now consisting of only two photons, will not longer be in its ground state but in an excited state despite the fact that one photon was removed.

Within this PhD thesis project, the doctoral candidate will be responsible for the entire process of designing and modelling the integrated circuits, their fabrication with the laser direct-write approach, and their characterization using quantum light.

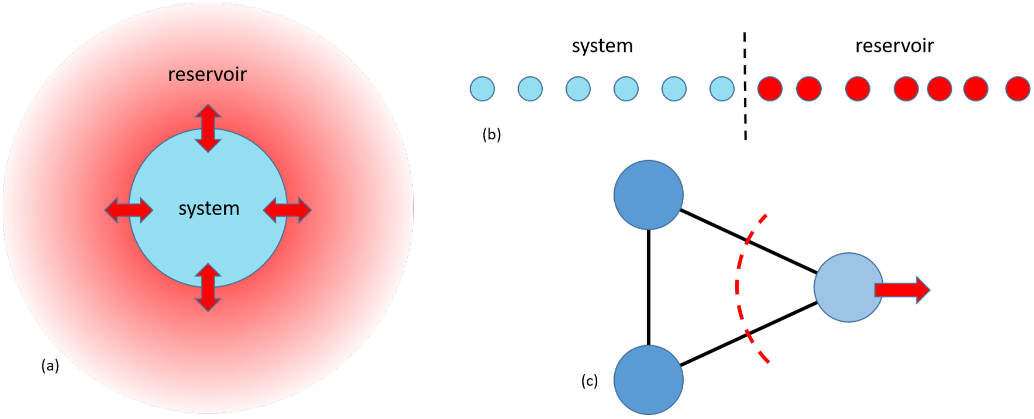

Figure 2: (a) A system, coupled to a thermal reservoir. (b) This will be simulated by a waveguide array with two regions: An ordered one representing the system, and a disordered one the reservoir at $T > 0$. (c) A quantum state, loosing a photons into the reservoir, becomes excited despite tha fact that a photon was lost.

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[2] Rev. Mod. Phys. 83, 771 (2011).

[3] Phys. Rev. Lett. 110, 150503 (2013).

[4] Phys. B 43, 163001 (2010).

[5] Opt. Lett. 35, 1172 (2010).

[6] Nature 560, 461 (2018).

[7] S. Deffner et al., "Quantum Thermodynamics: An introduction to the thermodynamics of quantum information," Morgan & Claypool Publishers (2019)