Abstract

Quantum devices hold the promise of many technological revolutions including quantum cryptography, unprecedented performance in some computational tasks including prime factorization, enhancement of machine learning, quantum simulations, etc. Some of the latter will have impact on applications such as computational drug discovery, design of new materials, etc. Their development is one of the major technical challenges of modern times, which requires in-depth understanding of underlying quantum phenomena as well as an engineering insight into the hardware platform used. In this thesis we have mainly focused on the first and wherever possible done the later as well. All the physical realizations and devices considered in this thesis are examples of open quantum systems, and a powerful formalism to study them is the Heisenberg-Langevin equations.

Photons being charge-neutral do not interact with each other and can have very long spatial and temporal coherence. An effective interaction between photons can be realized through their coupling to matter. We first investigate the role of optical nonlinearity in light propagation through two different one-dimensional open quantum electrodynamics (QED) lattices, namely a chain of qubits with direct coupling between the nearest neighbors and a chain of connected resonators to each of which a qubit is side-coupled. Using the more accurate truncated Heisenberg-Langevin equations (THLE) method we show a reduction of light transmission with increasing intensity in these lattices due to effective photon-photon interactions and related photon blockade mediated by nonlinearity in qubits. In contrast to the direct-coupled qubits, we find a revival in the light transmission in the side-coupled qubits at relatively higher intensities due to saturation of qubits by photons. Next, we compare the THLE approach to a quasi-classical analysis (QCA) recently used in the theoretical analysis of experimental observation of dissipative phase transition in a 1D circuit QED lattice. This system has relatively large qubit relaxation as well as intrinsic photon loss from every site of the medium. We are here interested in a 1D open QED system with negligible or no loss from the middle sites of it as we wish to understand the effects of interaction. We find that in absence of bulk dissipation the standard quasi-classical analysis fails to capture the reduction in light transmission due to effective photon-photon interaction. We specifically

notice that contrary to the results from the THLE, there is always some frequency that has perfect transmission within the QCA. We then devise a systemic method to modify the quasi-classical analysis to give much better results. In particular, we develop a simple scheme to find the complex interaction parameter for the modified QCA, which only uses single qubit analysis. Quite remarkably, the modified QCA works quite well when it is compared to the more accurate THLE even for larger systems. Unlike the QCA, the modified QCA is able to cause dissipation in the medium through the complex interaction parameter, which gives accurate results even at higher intensities at a much less computational cost than the THLE. Our work provides an insightful understanding of the role of excitation blockade on the transmission by proposing a simple calculation method to capture their effects.

While the models considered so far were motivated from experiments already carried out and hence should be within reach of similar experiments, in the second half of the thesis we have done a parallel development of quantum theory and preliminary device designs together. We next present the theoretical foundations of an analogous electromagnetically induced transparency (EIT) and absorption (EIA) which we have referred to as coupling induced transparency (CIT) and absorption (CIA) respectively, along with an exploration of the transition between these phenomena. We provide a concise phenomenological description with analytical expressions for transmission spectra and dispersion elucidating how the interplay of coherent and dissipative interactions in a coupled system results in the emergence of level repulsion and attraction, corresponding to CIT and CIA, respectively. This theory comprehensively captures the quantum phenomenon while modelling the microstripline loaded resonators and their couplings systematically. The model is validated through detailed device simulations of a hybrid system comprising a split ring resonator (SRR) and electric inductive-capacitive (ELC) resonator in planar geometry. We analyse two cases while keeping ELC parameters constant; one involving a dynamic adjustment of the SRR size with a fixed split gap, and the other entailing a varying gap while maintaining a constant SRR size. Notably, in the first case, the dispersion profile of the transmission signal demonstrates level repulsion, while the second case results in level attraction, effectively showcasing CIT and CIA, respectively. These simulated findings not only align with the theoretical model but also underscore the versatility of our approach. Subsequently, we expand our model to a more general case, demonstrating that a controlled transition from CIT to CIA is achievable by manipulating the dissipation rate of individual modes within the hybrid system, leading to either coherent or dissipative interactions between the modes.

We finally explore these peculiar phenomena in multi-mode coupled hybrid quantum systems by considering a tunable mode (TM) and several static modes (SMs). The individual SMs and TM are designed such that they show CIA, but upon coupling different SMs we observe a transition from CIA to CIT. The observation is attributed to the combined effect of input travelling photons from the bath/ cavity which is initiating the interactions between TMs and SMs of the hybrid quantum system. We have developed a robust quantum theory based formalism which is able to capture the transition between CIA to CIT and have the capability to explain the inter-transition (CIT to CIA) as well as intra-transitions (CIA to CIA, CIT to CIT etc.) in a multimode hybrid quantum system all with just linear approach. We have described two sets of hybrid systems, the first set is of three modes, 1TM coupled with 2SMs, and the second set is of four modes, 1TM coupled with 3SMs. Later we have generalised it for hybrid quantum systems having N number of modes. Controlled transition between CIT and CIA is an effect of both fundamental importance as well as potential applications in various devices. The results provide a pathway for designing hybrid systems that can control the group velocity of light, offering potential applications in the fields of optical switching and quantum information technology. Our finding and formulation that in a single hybrid quantum system we can achieve controllable inter-transitions and intra-transitions of CIT/CIA may open a tool and guidance for its application in quantum technology and quantum materials as the TMs/SMs may be well extended to other real/quasi-particles also.

Throughout the thesis we have studied several exotic quantum effects and developed a unified formalism based on Heisenberg-Langevin equations. We have particularly focused on experimental feasibility of all these effects and whenever possible developed suitable hardware designs and experiments as well. We hope the work of this thesis to be foundational, in particular in our research group, and building further on this future generations of students would be able to take the technology much farther.