Chapter 6

Summary and Outlook

Development of quantum devices is a challenging exercise 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. In chapters 2 and 3, we have explored transmission properties of photons through lattices of direct and side-coupled qubits respectively, where the qubits have on-site interaction. With the increase in intensity of incoming photons in a coherent state, both lattices develop effective photon-photon interactions and related photon blockade mediated by the on-site interaction at the qubits. For the direct-coupled qubits, at a single photon limit the transmission line-shape shows resonance peaks equal to the number of qubits in the system. With an increase in intensity the photon blockade occurs, which causes lowering of resonance transmission peaks until negligible transmission is observed at a very high intensity when the qubits get saturated by photons. The side-coupled qubits, at low intensity, also show resonance peaks with maximum transmission and a transmission minima at the qubit frequency. With an increase in intensity, the resonance peaks lower due to photon blockade along with the rise in transmission at the qubit frequency. At a very high intensity the qubits get saturated and their effects start to disappear resulting in a revival of photon transport in the lattice of side-coupled qubits. A non-monotonic behavior of transmission with increase in input intensity is observed for both homogeneous and inhomogeneous side-coupled qubits. We observed that the standard quasi classical analysis is not able to capture these nonlinear effects in the systems at high intensities. Our main contribution is a modification to the quasi classical analysis such that it agrees with the more accurate results for a set of parameters. With our modification, large system sizes can be effectively calculated with much less computational resources compared to the Heisenberg-Langevin approach.

In chapter 4, we have applied some of the insights that we have gained in the previous two chapters, i.e. chapters 2 and 3, towards some practical context and implementation of suitable devices. Many sets of theories are available to explain the phenomena we observe but surprisingly as far as we could judge, none of them are an actual representation of the devices generally used in the measurements. We have developed a comprehensive model resembling the actual experiments by considering all the major relevant parameters and components of the experiments including bath, inputs and outputs, etc. Solving the model and analysing the resonance frequencies and transmission profiles we have discussed some of the key insights from device physics perspective as well as from theoretical view point. We also have simulated suitable devices using the commercial full scale electromagnetic simulator CST studio suite and have verified our theoretical finding and model validity. For both kinds of interactions, coupling induced transparency (CIT) or coupling induced absorption (CIA) simulations and theoretical findings are in agreement. Later in the chapter we have discussed transition between CIA and CIT, and how various parameters are playing their role in determining the effective phenomenon. With that inspiration in hand, in the next chapter we have explored behaviour of these transitions in a single device.

In chapter 5, we have extended our insights from the previous chapter for multimode coupled hybrid systems in which multiple CIT / CIA phenomena are present in the system and transition amongst them have taken place. We have extended the theory for N modes and achieved the controlled transitions between the different effects. We have tested the theories for two cases. In case 1 we have considered three modes and started from two level attractions (LAs). We have tuned the parameters and finally reached one LA and one level repulsion (LR) while going through level absorption. In case 2 we have discussed four modes, started from three LAs, tuned the parameters and have reached finally having two LAs and one LR by passing through level absorption. The second case,which is a straightforward generalization of the first one, has been developed experimentally earlier. We are also in the process of doing further experiments to explore the rich physics of such devices.

The one-dimensional open QED lattices explored in the chapters 2 and 3 are complementary to an earlier experimental work in circuit QED lattices [Fitzpatrick et al., 2017], but we believe that the transport features observed by us are within the reach of recent experimental developments. Control over internal losses in the bulk of the lattice poses experimental challenges, and the current theoretical study can readily be extended to incorporate some intrinsic losses from the qubits and resonators. It would also be useful to examine the effects of inhomogeneity and optical nonlinearity systematically and explore the possibility of many-body localization [Pal and Huse, 2010; Roy et al., 2015; Singh and Shimshoni, 2017; See et al., 2019; Orell et al., 2019] in these systems. The modified quasi-classical analysis developed by us to study the nonlinear effects works for a wide range of parameters but it starts to deviate from more accurate quantum results at strong coupling. There is room for further improvement with a more systematic way of introducing the corrections such that the modified quasi-classical equations are applicable to a much broader range of parameters. Perhaps some renormalization procedure can also be developed that considers one qubit at a time with more variables and the rest of the system as renormalized parameters. This method can also be extended using the exact result of two site system to be applicable at higher coupling also. Further, it will be of interest to see how well the approximations developed by us is able to match the output spectra including the phenomena such as the Mollow triplet which are observed for such systems in the quantum analysis. These may lead to further insights for making better quasi-classical approximations. An earlier work has extracted an effective temperature by fitting the low frequency part of the spectra in quantum spin chains [Kilda and Keeling, 2019]. Similar fitting for the effective coupling may give important insights into more refined details of the blockade phenomena.

The theory developed in this thesis using Heisenberg-Langevin equation approach to solve the intricate dynamics is applicable for a wide range of quantum systems as the modes may be treated as any types of real or quasi particles. We have carried out planar device simulations for development of devices showing the effect. The generalized model developed by us captures effects that arise through coupling of linear modes. However there are genuinely nonlinear phenomena such as EIT etc., that cannot be explained by such models. Extending this generalized approach to include nonlinear phenomena is a promising future direction which has already been started by our group. Building on my work which is described in this thesis, our group has theoretically studied magnon-magnon coupling and its control in nanomagnets [Kashid et al., 2024], Purcell effect in cavity magnonics [Verma et al., 2025] etc., as well as carried out experimental works on multi-mode chiral resonators, observation of bound state in the continuum in coupled resonators [Tunwal et al., 2025], characterization of coupling strength with thickness and dielectric properties, etc. Further several aspects of cavity magnonics are planned to be studied in near future both experimentally and theoretically. Though these complementary simulations and experiments are far from the quantum regime, they should be seen as first steps towards observing these phenomena in quantum devices. We are also looking forward to gate implementation, non-reciprocal transport, quantum transducer and quantum information processing using simple planar devices.