論 文 の 内 容 の 要 旨

論文題目　Fabrication of Tunable-Q Photonic Crystal Nanobeam Cavities for the Control of Light-Matter Interaction
(Q値可変フォトニック結晶ナノビーム共振器の作製と光電子相互作用の制御に関する研究)

氏　　名　　太田　竜一

Photonic crystal (PhC) nanocavities have been investigated as fascinating platforms to build integrated optical devices and to study fundamental physics of the light-matter interaction in cavity. Strong light confinement in both of real space and frequency space enable to dramatically enhance the overlap of the field distribution of cavity modes to nano emitters. In addition, emission rate and collection efficiency from cavity modes can be engineered by modifying PhC pattern. So far, PhC nanocavities are widely studied to enhance optical property of materials toward extremely efficient lasers and solar cells, and to construct quantum information system in solid.

Recently, dynamical control of the property of PhC has been of great interest because of their capability to improve the functionalities for integrated optical devices and open the novel field to study the light-matter interaction. In particularly, in-situ control of quality (Q) factor in PhC nanocavities is one of the promising objectives, since it enables photon trapping and releasing within a micrometer scale region, as well as tunable spectral filtering. The first demonstration of Q factor control and subsequent experiments to manipulate the

light-matter interaction had been reported by injecting local heat or extra carriers which modify the refractive indexes around the cavity. However, several problems still remain for realizing a larger tuning range of Q factor and resulting control of the light-matter interaction. The biggest problem is that the generated heat and carriers hardly degrade the controllability of Q factor and the optical properties of materials. Avoidance of this problem is essentially difficult in the conventional way. It is the time to break through the limitation by a new approach.

In this thesis, one dimensional PhC nanocavities, called PhC nanobeam cavities, in micro electro mechanical system (MEMS) is investigated to control their Q factors. Q factor of PhC nanobeam cavity is controlled by changing the gap distance between the cavity and an adjacent waveguide. The cavity and the waveguide are connected to MEMS actuators respectively, which separate the gap distance without any undesired effects including additional heating and generation of extra carriers. In this thesis, Q factor change from 3,500 to 14,000 with a voltage of 17 V is experimentally demonstrated. The combination of the wide range tunable-Q cavity and self-assembled quantum dots (QDs) enable to dramatically change the coupling between photon and exciton in the system.

In chapter 2, fundamental physics about PhC nanocavities, QDs and the light-matter interaction in the cavities are discussed. Based on Jaynes-Cummings model, two different regimes of the interaction in the QD-cavity coupled system are explained. It also indicates that one of the critical parameter, which governs the light-matter interaction in cavity, is Q factor of PhC nanocavities.

In chapter 3, design and fabrication procedure for high Q PhC nanobeam cavities without MEMS are explained. Demonstration of high Q PhC nanobeam cavities leads a wide range Q factor control by combination with MEMS actuators. Thanks to parabolic modulation of air-hole distances, intrinsic (calculated) Q factor of isolated PhC nanobeam cavity exceeds 10^7. After the careful optimization of fabrication process, Q factor of 44,000 is experimentally achieved in PhC nanobeam cavity incorporating QDs.

Measurement setup and fundamental characteristics of PhC nanobeam cavities are discussed in chapter 4. By tuning the resonant wavelength of the cavity mode to that of a single QD, vacuum Rabi splitting of 226 μeV is observed, which confirms the coupled system is in strong coupling regime. In weak coupling regime, low threshold lasing in PhC nanobeam cavity is also demonstrated. These experimental results indicate that the coupled systems of QD-PhC nanobeam cavity enable to dramatically change the light-matter interaction by control of its Q factors.

In chapter 5, design and fabrication techniques for electro mechanically controllable PhC nanobeam cavities are described. Fabrication procedure of electro mechanically controllable PhC nanobeam cavities becomes much complicated and difficult than that of isolated PhC nanobeam cavities. Especially, these movable structures are easily broken down in wet etching process due to the strong surface tension of water. However, optimization of each process and introduction of boiling technique drastically increase success rate.

In chapter 6, wide range Q factor control and modulation of the light-matter interaction are experimentally demonstrated. Q factor is continuously controlled from 3,500 to 14,000, which is the largest control range of Q factor in PhC nanocavities incorporating QDs. Modulation of emission lifetime of QD in a PhC nanobeam cavity is also observed by changing the Q factor. Furthermore, in-situ switching of the coupling regimes is discussed in this chapter.

Resonant wavelength shifts of the cavity mode are observed in the Q control operation, which induce a detuning between the QD and the cavity resonance. Therefore, novel designs to reduce the resonant wavelength shift with keeping a large tuning range of Q factor are expected for more complicated control of the light-matter interaction. For this purpose, theoretical analysis of coupled mode equations in cavity-waveguide system is investigated in chapter 7. Good agreement between theoretical model and FDTD calculations reveals that variations of Q factor and resonant wavelength of cavity mode are attributed to the coupling of waveguide modes. This finding indicates that the voltage dependence of Q factor and resonant wavelength shift can be manipulated by tailoring the dispersion of the waveguide.

Finally, conclusion of this thesis is presented in chapter 8. Significances of the results in this thesis and an outlook for future prospects are discussed in this chapter.