博士論文(要約)

Study on Fabrication of Three-Dimensional Photonic Crystals using Plate-Insertion Method and their Applications

(プレート差込方式による三次元フォトニック結晶の作製とその応用に関する研究)

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Three-dimensional photonic crystals (3D PCs) are artificial photonic media with a three-dimensional periodic refractive index which enables complete photonic band gaps (cPBGs): frequency ranges where light propagation is prohibited regardless of the wave vector and polarization, even for vacuum fields. This complete inhibition has various potential applications such as omni-directional reflectors or storage of energy via light emitters inside 3D PCs. Introducing crystal defects into 3D PCs further allows implementation of various photonic devices, such as optical waveguides or nanocavities at the optical wavelength scale, which lead to an ultimate goal of densely integrated 3D photonic circuits.

Towards this ultimate goal, fabrication techniques for 3D PCs with cPBGs at near infrared wavelengths have been developed in the course of demonstrating proof of concepts. These devices fabricated thus far have been either passive photonic devices, such as optical waveguides and cavities, or active photonic devices, such as nanocavity lasers and light emitting diodes. However, in order to realize a densely integrated 3D photonic circuit, it is necessary to simultaneously integrate both passive and active photonic components in a single 3D PC chip. This necessitates the enlargement of the 3D PC size so as to integrate more components onto a single chip. In the case of fabrication by micro-manipulation technique, the only method that has enabled any demonstration of 3D PC nanocavity laser so far, the small size of the 3D PC has hindered this integration of photonic devices and nanocavity lasers.

This thesis provides an important key to solve this issue. To enlarge the volume of 3D PCs, plate-insertion method is introduced into the current micro-manipulation technique. This enabled the integration of both photonic waveguides and nanocavity lasers within a single 3D PC, and will allow integration of various photonic devices, whether active or passive, leading to the realization of various functionalities in integrated photonic circuits. In addition, this thesis investigates novel 3D PCs, both from the fundamental scientific view and from its applications to photonic integrated circuits.

In chapter 1, previous research on 3D PCs towards photonic integrated circuits is reviewed. Then the research objectives and outline of this thesis is shown.

In chapter 2, prerequisites of PC fundamental theory are summarized. First, an intuitive description of PCs and the physical origin of PBGs is discussed, followed by more detailed descriptions of PBGs using photonic band diagrams, and cPBGs in 3D PCs. Next, crystal defects in PCs, which functionalize PCs, are discussed. Finally, several numerical analysis methods used in this study for investigating optical properties of 3D PCs is summarized.

In chapter 3, enlargement of the 3D PC compared to previous work is experimentally demonstrated using the current micro-manipulation technique. The experimental methods, results and current limitations are discussed. The volume is increased by approximately 5 times, almost doubling the quality factors Q of nanocavities embedded inside the 3D PCs, resulting in a world record of $Q \sim 66{,}000$ among 3D PC nanocavities.

In chapter 4, "plate-insertion method", a novel stacking method to increase the number of layers, applicable to the micro-manipulation technique, is proposed and demonstrated. The overview, expected advantages together with their proof, experimental methods are explained in comparison to the previous stacking method. The layers in the 3D PCs was roughly doubled: in conjunction with the techniques introduced in chapter 3, a total of 10 times increase in volume was demonstrated compared to previous work. This method maintains the benefits of micro-manipulation technique: lasing oscillations of 3D PCs.

In chapter 5, simultaneous integration of waveguide structures and nanocavity-based light sources into a single 3D PC is experimentally demonstrated for the first time using the plate-insertion stacking method. In the first half, integration of straight waveguides with nanocavity based light sources is demonstrated. In the latter half, nanocavity based light sources are integrated with 3D waveguides to successfully achieve 3D guiding of laser light within a single 3D PC. These are the first demonstrations of integrating both active and passive photonic devices within a 3D PC.

In chapter 6, novel 3D PCs are theoretically studied with a goal of adding novel functions to photonic integrated circuits. This thesis focuses on two 3D PCs with layer-by-layer structures, and their light confinement in planar directions. Also, by investigating a wider range of 3D PC structures, novel 3D PCs capable of obtaining cPBG at shorter wavelengths were discovered.

In Chapter 7, this thesis is concluded, followed by outlooks and future prospects.