博士論文（要約）

Design and Fabrication of Three Dimensional Photonic Crystal for Guiding and Localization of Light

（光導波・局在機能を有する三次元フォトニック結晶の

設計と作製に関する研究）

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Possessing spatial periodicity in the dielectric constant, photonic crystals (PCs) can prevent light from propagating in certain directions with specified frequencies. This frequency range is referred as photonic bandgap (PBG). In 1987, the concept of photonic crystal was brought into the optical research field. Many researches, by utilizing PC structures, have been conducted to improve the performance of optical components. Most of these researches focused on two-dimensional (2D) PCs, particularly the so-called 2D PC slabs, which consisted of thin dielectric plate with periodic arrangement of holes. Properties of the 2D PC slabs were developed with a rapid speed compared with three-dimensional (3D) PC because of the ease of fabrication. However, from the practical point of view, light gets loss to the third direction of 2D PCs easily because the dielectric constant only varies in two directions. On the contrary, the dielectric constant of 3D PCs varies in all directions. 3D PCs, which possess a complete photonic bandgap (cPBG), are possible to control light of all polarizations in all directions. Therefore, 3D PCs have a potential to operate light in a 3D structure. This potential, which allows us to realize 3D optical circuit, makes 3D PCs more meaningful to investigate.

However, the performance of optical components in 3D PCs is still far behind that in 2D PCs. For instance, single mode operation bandwidth of 3D PC waveguide (PCW) still needs to be expanded. The quality factor (Q) of 3D PC nanocavity is also expected to be improved further because it is still far behind that of 2D PCs. Thus, in order to fully utilize the advantages of 3D PCs, researches on these issues discussed above are strongly expected.

Aiming to address these issues, original research work on designs of PCW and nanocavity in 3D PCs are presented in this thesis. Experimental work to demonstrate the usefulness of our design is also presented.

After a brief introduction of the research background and objectives of the research in Chap. 1, basic physics of PCs that are necessary for understanding the research are introduced in Chap. 2. Types of PCs that classified by dimensionalities are introduced. After the introduction of several types of 3D PCs, the woodpile structure, one of the 3D PCs, is described in details as it is the basic structure of all the work in this thesis. Then, varies of fabrication methods of 3D PCs are discussed. Finally, the way of manipulating light with PCs, introducing defect into PC structures, is discussed.

The fundamentals of plane wave expansion (PWE) and finite-difference time-domain (FDTD) methods, which are computational methods used in this thesis, are described in Chap. 3. By using these two computational methods, how to obtain important characters of PC structures are discussed. For instance, calculation on band diagram of PC structure, frequency of cavity mode, Q and mode volume of nanocavity structure are discussed.

In Chap. 4, a design of silicon 3D PCW is reported. Tuning the width of the line defect allows the waveguide to support two guided modes, which enable single-mode propagation ~98.7% of the cPBG. In addition, we demonstrate that the frequency ranges for single-mode propagation can be extended to almost the entire range of the cPBG by further tuning the thickness of the layers. The wide ranges of available frequencies for single mode propagation enable flexible design of 3D PC components and would provide a route towards future 3D photonic circuits.

A nanocavity is designed to improve the Q of 3D woodpile PC in Chap. 5. The Q of the nanocavity embedded in a vertically mirror-symmetric woodpile structure, which can be realized by changing the stacking sequence of layers above the cavity layer of an ordinary woodpile structures, is discussed. A Q of 1.7×10^5 of the nanocavity embedded in the mirror-symmetric structure can be obtained. This is ~3.6 times as high as the maximum Q of the same size of the nanocavity embedded in an ordinary woodpile structure. Compared with other designs of 3D PCs at same level of Q, our design can improve the Q with a smaller structure volume.

Finally, in Chap. 6 experimental work for investigating the effect of mirror symmetric woodpile structure on cavity Q as discussed in Chap. 5 is presented. Both of nanocavity structures in a mirror symmetric woodpile and an ordinary woodpile are fabricated by using micromanipulation technique. A square-shaped defect cavity embedded in the mirror symmetric woodpile structure with 25 layers exhibits a cavity mode with Q ~4,000, which is larger than that of the nanocavity design in the ordinary woodpile (~3,100).

At last, the main achievements presented in this thesis are summarized. The outlooks for future research are also given in Chap. 7.

The results obtained in this thesis provide an important step towards the complete manipulation of light in nanostructures.