Spectral Characterization of Two-Dimensional Photonic Crystal Slabs by Using Midinfrared Angle-Resolved Reflection Measurement

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（角度分解反射測定による２次元フォトニック結晶スラブのスペクトル評価）

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論　文　内　容　の　要　旨

Quantum cascade lasers (QCLs), known as novel semiconductor lasers based on intersubband transitions, have been tremendously developed because they can cover broad spectral emission at midinfrared wavelengths from 3 to 20 μm. In this spectral range, we can observe the rotational absorption peaks of various kinds of harmful and toxic gases such as nitrogen monoxide (NO), carbon monoxide (CO), and carbon dioxide (CO_2). Therefore, the mid-IR QCL is regarded as one of the most promising laser candidates for gas sensing and analysis.

There are two typical architectures of semiconductor lasers, i.e., edge-emitting lasers (EELs) and vertical cavity surface emitting lasers (VCSELs). In the EELs, light waves are tightly confined in the surface-normal direction more strongly than in the in-plane direction. Hence, the output beam tends to exhibit a highly asymmetric cross-section and a large beam divergence. VCSELs have a different architecture which generates a less divergent symmetric beam. However, standard VCSELs tend to undergo a limited output power as small as several milliwatts, when operated in a single mode. To solve the VCSELs' drawback, photonic crystal surface-emitting laser (PCSEL), a new type of semiconductor lasers that utilize photonic crystals integrated on top of the active layer, has been proposed. The application of PC architectures to QCL resonators is expected to serve as a way of creating midinfrared lasers with a good beam quality.

In PCSEL, the principle of the laser action relies on the zero group velocity of light at photonic band edges, which results in strong in-plane feedback inside the PC slab. Moreover, when the band edges are formed at the Γ point in momentum space, radiation into free space purely out of plane, i.e., normal to the slab. Hence, careful PC design that realizes perfect resonance between the band-edge mode and the material gain frequencies is essential for achieving vertical emission. The measurement of in-plane dispersion relations is thus frequently performed to verify optimum conditions in fabricated devices.

A technique commonly used to characterize photonic band structures in PCSEL devices is the angle-resolved observation of subthreshold luminescence spectra. The technique is widely used for the characterization of visible and near-infrared wavelength PCSELs. However, this technique cannot be applied to midinfrared wavelengths due to the limited sensitivity of infrared detectors. To develop midinfrared PCSEL, an alternative scheme is required for characterizing the PC slabs.

In this thesis, we developed high-resolution angle-resolved reflection measurement techniques to observe photonic band structures in the midinfrared region. First, we applied these techniques to the study of standard silicon-on-insulator (SOI) based triangular-lattice PC slabs that have C_{6v}-symmetry with two different radii, r = 530 and 560 nm. We observed the angle-resolved reflection spectra, and then, the photonic band structures in the vicinity of the Γ point. We successfully assigned the eigenmode symmetry, and clarified the formation of photonic Dirac cones, which were materialized by the effective degeneracy of the Γ point modes.

Then, we applied our angle-resolved reflection technique to the characterization of actual PCSEL devices formed of In(Ga,Al)As/InP based QCL multilayer structures. We identified complex PC modes in the vicinity of the Γ point in square-lattice PC slabs with C_{4v}-symmetry with the aid of rigorous polarization selection rules derived by the group theory.

Next, we studied a variety of PC slabs that have different pillar shapes and filling factors. In particular, we compared the reflection spectra for the sample with C_{4v}-symmetry and that with a symmetry lower than C_{4v}. The results imply that the lower symmetry PC slabs enable efficient light extraction.

This thesis consists of six chapters. In Chapter 1, the midinfrared QCL application and the development of semiconductor lasers are briefly reviewed. Then, the progress of PCSELs and the technique to observe photonic band structures are discussed. The remaining challenges and the purpose of the thesis are specified.

Chapter 2 presents the schematic diagram of the optical setup for angle-resolved reflection measurement. The optical setup is installed inside the compartment of an FT-IR spectrometer. The performance test by measuring reflection intensity as a function of incident angle is presented.

Chapter 3 discusses the angle-resolved reflection measurement of PC slabs that have a relatively high refractive index contrast. The experimental results of SOI triangular-lattice PC slabs with C_{6v}-symmetric structures with the different radius of air holes are presented. The spectral width analysis results reveal the formation of photonic Dirac cones.

Chapter 4 verifies in-plane dispersion relations in the vicinity of the Γ point for C_{4v}-symmetric PC slabs with circular pillars. The peak shift as a function of lattice constants appears in the reflection spectra at normal incidence. The Q factors of wave guide modes are evaluated semi-quantitively.

In Chapter 5, we fabricate PC slabs with different filling factors and pillars. The peak intensities for the PC slabs with C_{4v}-symmetry (circular pillars) and those with a symmetry lower than C_{4v} (triangular and pentagonal pillars) are observed at normal incidence. The higher intensity for the pentagonal pillars is obtained because of its higher filling factor. Moreover, since the sample with pentagonal pillars has a symmetry lower than C_{4v}, several split peaks are observed in the spectra near the Γ point. Thus, this sample is expected to show efficient light extraction.

In Chapter 6, we summarize the experimental findings and discuss future works.