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Photonic Crystals and Their Applications

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1. Introduction

Much interest has been drawn in photonic crystals (PCs) in which the refractive index changes periodically. A photonic bandgap is formed in the crystals, and the propagation of electromagnetic waves is prohibited for all wave vectors. Various important scientific and engineering applications such as control of spontaneous emission, zero-threshold lasing, very sharp bending of light, trapping of photons, and so on, are expected by utilizing the photonic Bandgap (PBG) and the artificially introduced defects and/or light-emitters. In this conference, the present status of photonic crystals and their applications will be described by showing some examples of our recent studies.

2. Light-Emission Control by 3D Photonic Crystals

3D photonic crystals have, needless to say, the ability of perfect control of light propagation and/or emission. We previously succeeded in developing complete 3D photonic crystals with sufficient bandgap effects at near-infrared wavelengths (1.3~1.55μm) based on a method where III-V semiconductor stripes are stacked with the wafer-fusion and the laser-beam assisted very precise (a few tens nano-meter scale precision) alignment [1]. We then started investigations of effects of introducing various defects and/or light-emitters into the 3D photonic crystals [2]. Here, in order to show one example of such studies, we report on effects of 3D photonic crystal on the suppression of spontaneous emission, which is an important to realize novel devices such as so-called zero-threshold semiconductor laser.

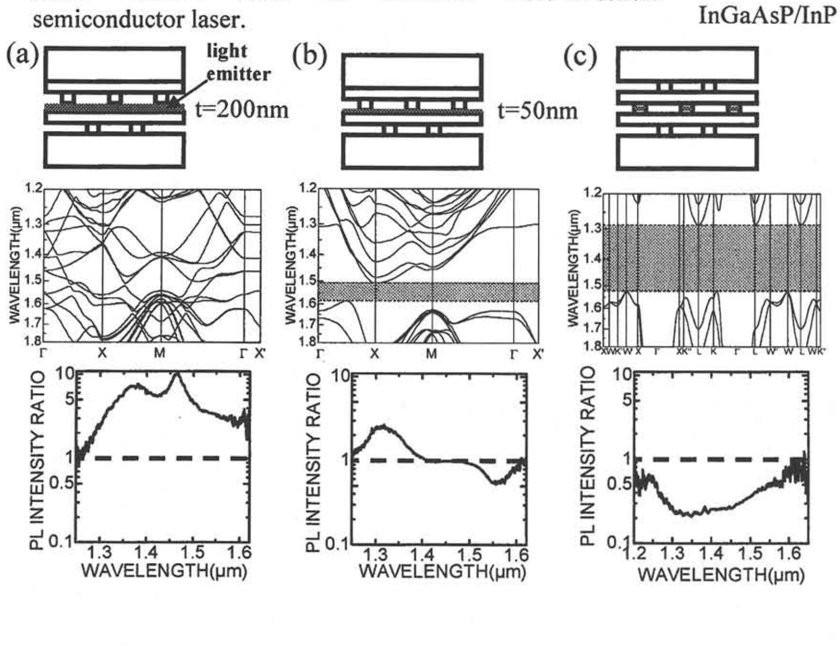

Fig. 1. 3D PCs with light emitters, corresponding band structures, and photoluminescence spectra. (a) (b)The light emitters with planar geometry are inserted in the middle of 4-layer PCs. The thickness of the light emitter is 200 and 50 nm for (a) and (b), respectively. (c) The light emitter possesses stripe geometry with the same structural parameters as the surrounding photonic crystal layers.

Figures 1(a)-(c) show three different samples of 3D photonic crystals. The most ideal method of introduction of light emitters to suppress their spontaneous emission is shown in Fig.1(c), where the stripe-geometry III-V semiconductor light-emitting layer with the same structural parameters as the surrounding photonic crystal layers is introduced at the center of the crystal. By this method, the refractive index distribution of the crystal is not disturbed so that the bandgap width remains the same as before the introduction of the light emitters. In addition to fabricating such an ideal structure, we also fabricated the samples as shown in Figs. 1(a), (b), where thin flat light emitters are introduced at the center of the crystals. The thickness t of the light emitter (LE) is 200, 50nm, respectively. Since the light emitter introduced disturbs the periodicity of the crystal, it creates allowed states inside the bandgap and the bandgap disappears for the case of Fig. 1(a), or becomes narrower for the case of Fig. 1(b).

We measured a photoluminescence (PL) spectrum from the light-emitter introduced in each of the three samples and show the results at the bottom of Figs. 1(a)-(c), respectively. We also prepared three reference samples for each of the three samples shown in Figs. 1(a)-(c). Each reference sample possesses a light-emitter with the same geometry as each of the samples shown in Fig. 1(a)-(c) but is sandwiched by un-patterned layers instead of photonic crystals. Each of the PL spectra measured is then normalized by the PL spectrum of the corresponding reference sample. The light-emitter contains a three period InGaAsP/InP multiple-quantum-well (MQW) structure grown by metal organic vapor phase epitaxy (MOVPE) and emits light including the wavelength range of 1.3~1.55 μm. A laser with wavelength of 900 nm, which is transparent for the PCs, was used to pump the light emitter and the PL measurement was performed at room temperature. It is seen at the bottom of Fig. 1(a) that the PL intensity from PC with LE of t=200 nm is enhanced as compared to the reference rather than suppressed. The peak of enhancement factor is almost 10. This is considered due to the effect of the resonant cavity formed by thick light-emitter inside the PC. On the other hand, in the case of Fig. 1(b), there exist a wavelength range where the spontaneous emission is enhanced and a wavelength range where it is suppressed. The wavelength range where spontaneous emission is suppressed corresponds well to the full bandgap of PC. This suggests that effects of the PBG are being observed. For the wavelength range where spontaneous emission is enhanced, correspondence to the existence of the allowed states can be seen. Finally, for the case of Fig. 1(c), we can see a suppression of spontaneous emission in the wavelength range of the bandgap (1.3~1.55μm). The above results imply a possibility of spontaneous emission control by the 3D PCs, and encourage us to introduce a defect with light-emitting capability to show that the enhancement of light emission occurs at the defect part but suppression occurs at the portion without the defect, which will be also described briefly at the conference.

2. Functional Device by 2D Photonic Crystals

In spite of the lack of complete photonic bandgaps, it is possible to construct a variety of useful functional devices using 2D photonic crystals. We previously reported very interesting phenomena in 2D-PC slabs[3], where photons propagating in the line defect waveguide are trapped by the point defect, which emit them to free space, when the photon frequency matches to the defect frequency. Based on the phenomena, we fabricated surface–emitting channel–drop–filtering devices which operate at optical communication wavelengths. We also investigated the reverse function of the devices, where photons propagating in the free space are trapped by the point defect and transferred to the waveguide. Such phenomenon is very interesting and is applicable to a surface–inputting channel-add-filtering device.

The sample investigated was an air-bridge type triangular lattice PC slab made of 0.25μm-thick Si. The lattice constant (a) of the PC and the radii of air holes were 0.42μm and 0.29a, respectively. A line defect waveguide was introduced along Γ-J direction, and an acceptor type point defect (radius 0.53a) was introduced nearby. At first, we carried out a channel-drop-filtering experiment. Photons were injected from the waveguide edge, and the light power emitted from the other facet and that emitted from the point defect were measured and plotted in Figs.2(a) and (b), respectively. The transmittance and drop spectra show negative and positive peak at 1557 nm, respectively, which clearly indicates that the light propagating in the waveguide is dropped via the point defect mode. The dropping efficiency was estimated from the transmittance at 1557 nm, and was found to be more than 45%, which is considerably high since the theoretical maximum for the current structure is 50%. The oscillation patterns observed in the transmittance spectrum are due to a Fabry-Perot interference between the both waveguide facets. In addition, the oscillation patterns in the drop spectrum were found to be due to a composite interference between the point defect itself and two waveguide facets.

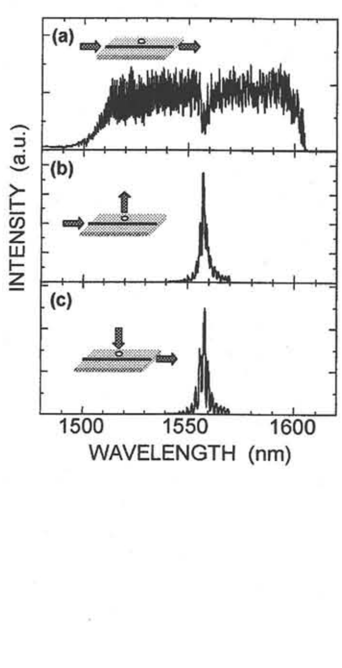

Fig.2 (a) Transmittance, (b) drop, and (c) add spectra measured for the sample. Insets are schematic drawings showing configurations used for each measurement.

Next, we made reverse experiment, where light was focused on the point defect directly from free space. Light emission from the waveguide edge was clearly observed when the light beam position was fitted to the defect position. The spectrum of the edge emission was measured and plotted in Fig. 2(c), which exhibits a clear resonant peak at 1557 nm. The agreement between Figs. 2(b) and (c) clearly indicates that the light can be added to the waveguide via the point defect mode. The efficiency to add the light into the waveguide was almost as same as the light injection efficiency from the waveguide edge. We think it is very interesting that a cavity made of a hollow air hole can capture light propagating in free space and can change the direction of the propagation. The polarization dependences of the add and drop operations were also measured and were found to be identical.

3. Summary

3D photonic crystals and their effects on the light-emission have been described at first. Strong evidence to show that the suppression of spontaneous emission occurs at the full bandgap region has been successfully obtained. Next, 2D photonic device with the channel add/drop function has been successfully demonstrated. We consider that 3D crystal is very important for ultimate control of light and step-by-step study should be continued, while 2D crystal is very useful for the actual applications and the proto-type device will soon appear.

Acknowledgments

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References

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