

# Photonic Crystals — An Introduction

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## 1. Introduction

This presentation introduces a unique world of photonic crystals. They are artificial multi-dimensional periodic structures with a period of the order of optical wavelength. They have many analogies to solid state crystals. The most important one is the *band of photons*, which is a powerful theory for the understanding of light behavior in a complex photonic crystal structure. It enables us to create the *photonic bandgap* and the *localization of light*. They have great potentials for novel applications in optics, optoelectronics,  $\mu$ -wave technologies, quantum engineering, bio-photonics, acoustics, and so on. Here, I will outline these fundamental features of photonic crystals with their progress of research.

## 2. Structures and Photonic Bands

Figure 1 shows semiconductor photonic crystals with nanometer order periods and corresponding Brillouin zones (unit cells in a reciprocal lattice space, which represents the spatial Fourier spectrum of the photonic crystal structure). They are categorized by the dimension of periodicity. Figure 2 shows examples photonic bands, the dispersion relations between the time frequency and the spatial frequency (wave number  $k$ ). Such bands are obtained by the similar procedure to solid state physics theory, i.e. a master equation (Maxwell's wave equation) is transformed into an eigenvalue equation with a periodic boundary condition and solved by computation. Due to the rigorous treatment of vectorial property of electromagnetic fields, photonic bands precisely predict the behavior of light.

## 3. Unique Phenomena

One of the most important discoveries is the existence of a photonic bandgap, which is a forbidden

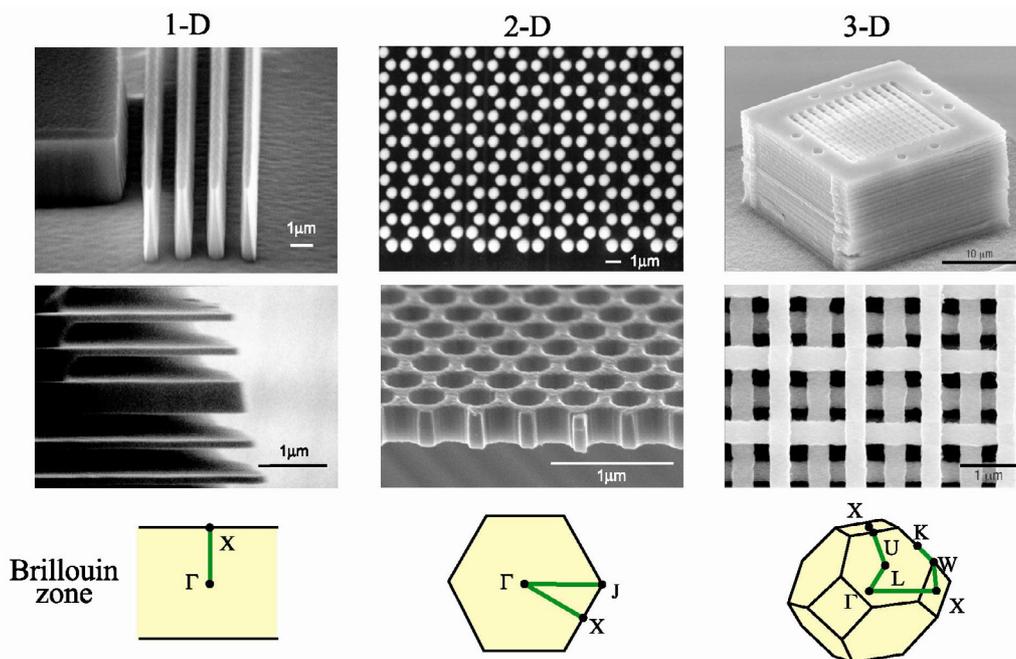


Fig. 1 Various photonic crystal structures of different dimensions and corresponding Brillouin zones.

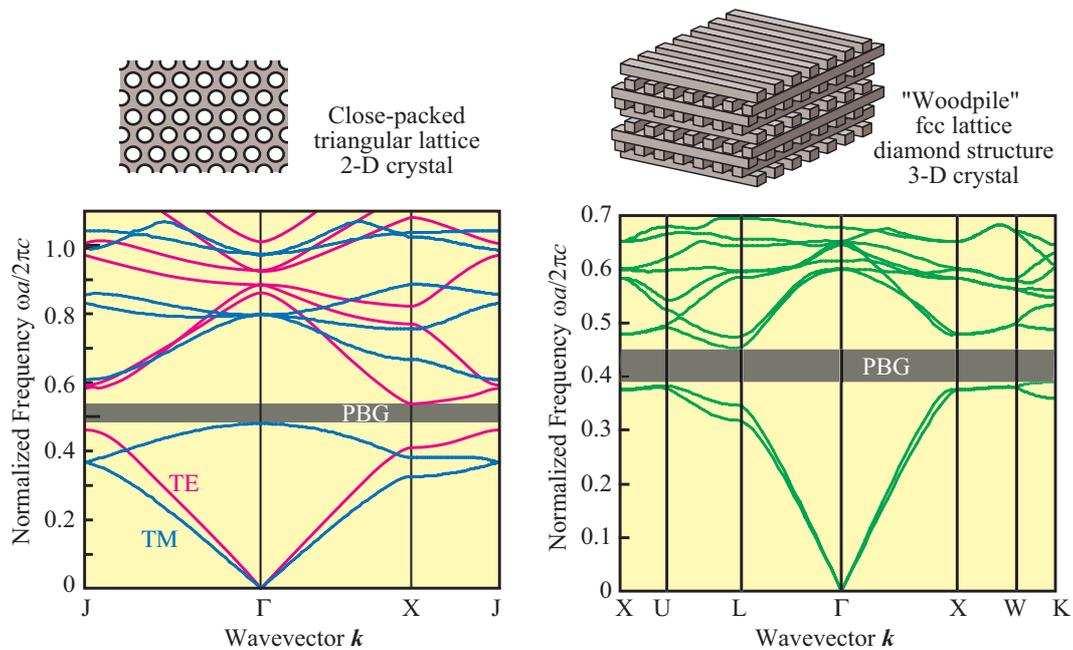


Fig. 2 Photonic bands of 2-D and 3-D photonic crystals.

gap of photons. In this gap, light cannot enter the crystal and electrons cannot emit photons inside the crystal. The doping of an impurity optical atom or defect creates the opposite situation, the strong localization of a resonant photon. These phenomena will allow a perfect control of light propagation and radiation. Since the photonic bandgap crystal acts as an insulator of light, flexible and dense photonic circuit similar to an electronic LSI will be realized. The light velocity will be changed from vacuum velocity  $c$  to zero (stopping condition), so the light matter interaction will be arbitrarily controlled. The spontaneous emission, which is normally dominated by the random thermal process, will be artificially engineered so that it perfectly contributes to a useful emission.

Other unique phenomena are also found in complex photonic bands. A careful design of a crystal provides the superprism phenomenon that indicates an extraordinary large steering of light beam, a guiding of light beam with no waveguide structures, a negative refraction that enables peculiar focusing and imaging of light, the left-handed light propagation supported by the negative permeability and permittivity, an extraordinary large group velocity dispersion that manipulates an optical pulse, etc.

#### 4. Progress of R& D

The establishment of fabrication technologies is first required in this field, but in these years, some semiconductor process techniques, nano-manipulation techniques, self-organization techniques, holographic techniques, etc., reached a sufficient level for the demonstration of a photonic bandgap and other phenomena, as seen in the next two presentations. Now, a number of worldwide groups are studying their applications to light sources including nanolasers, waveguide components for a next era functional circuits by photons, and passive components and fibers partly commercialized.

#### Important References

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# Photonic Crystals

## --- Recent Progress ---

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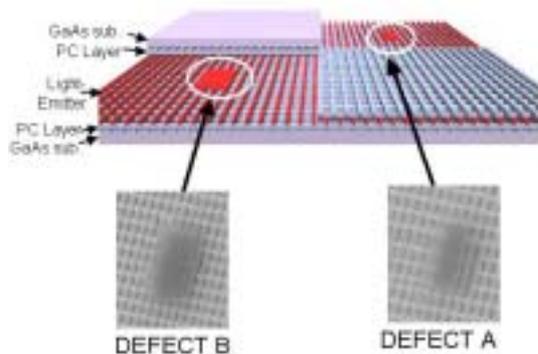


### 1. Introduction

Much interest has been drawn in photonic crystals, which are novel nanostructures for light. 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 light emission and propagation, trapping of photons, etc, are expected to be realized by utilizing the photonic bandgap and artificially introduced defects and/or light-emitters. In the following, I will review the recent progress of photonic crystals by focusing our activities.

### 2. 3D Photonic Crystals

We previously developed 3D photonic crystals with a complete bandgap at near-infrared wavelengths (1~2 $\mu$ m) and recently succeeded in introduction of various artificial defects and/or light-emitters into the crystals. In this symposium, we at first explain the control of light-emission and propagation by 3D photonic crystals. Fig.1 shows one example, where artificial defects and light-emitters are introduced simultaneously into 3D crystal. It has been found that the light-emission is suppressed at the position where artificial defects are not introduced, while that is enhanced at the positions where the defects A and B are introduced.



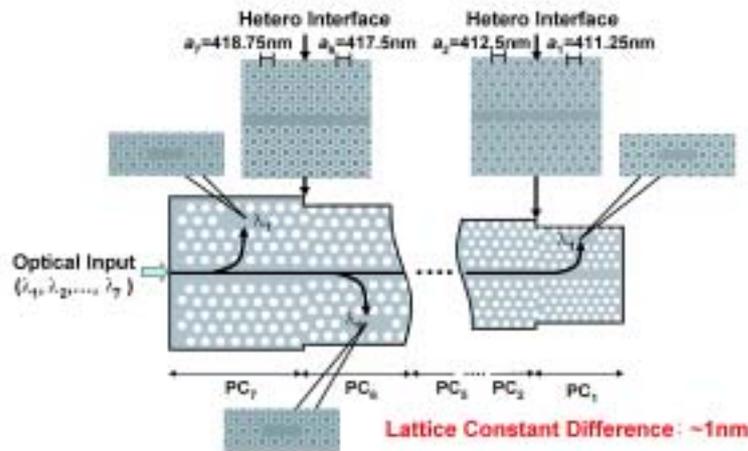
**Fig.1:** Schematic structure of 3D photonic crystal with light-emitting layer (red). Two isolated defects labeled A and B are also introduced. The insets below show SEM photographs of defects A and B observed from an oblique direction after stacking two GaAs layers. It has been found that the light-emission is suppressed at the position where artificial defects are not introduced, while that is enhanced at the positions where the defects A and B are introduced.

### 3. 2D Photonic Crystals

2D photonic crystals are also very promising. Strong confinement (or control) of photons can be possible by utilizing 2D photonic bandgap effect for the in-plane direction and refractive index contrast for the vertical direction. The important examples of light control by 2D photonic crystal are explained in this symposium.

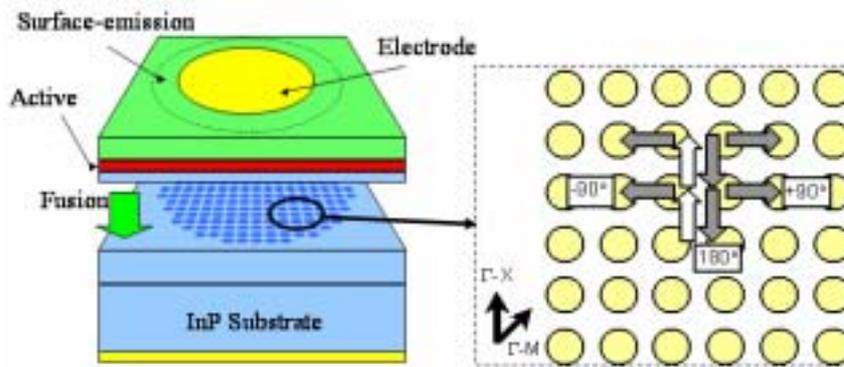
(1) Trapping of Photons: Artificial line- and point-defects are introduced into 2D photonic crystal slab. The point-defect traps the photons which propagate through the line-defect waveguide and emits them to free-space. The phenomenon is very interesting for the actual application to an ultra-small optical device with a function of dropping (or adding) photons with various energies from (or into) optical communication traffic (fiber). Since the photons are confined in an ultrasmall point defect cavity, the other various

important applications such as bio- and environmental-sensing, atom trapping, nonlinear phenomena, and so on can be expected. Recent our findings of two new concepts ‘In-plane Hetero Photonic Crystals (Fig.2)’ and ‘Ultra high Q photonic Nanocavity’ will accelerate these various applications.



**Fig.2.** Schematic structure and SEM pictures of photonic nanostructure devices based on a new concept of ‘In-Plane Hetero Photonic Crystals’. Seven photonic crystals (PC<sub>7</sub> to PC<sub>1</sub>) with different lattice-constants are connected sequentially. When the photons with different wavelengths are introduced into the waveguide, photons with different wavelengths are emitted from the point defects in different photonic crystals.

(2) Coherent 2D Lasing Action and Application to Novel Surface-Emitting Laser: At the band-edges of the photonic band diagram, the group velocity of light becomes zero. It indicates that standing waves are formed at the band-edges. By utilizing this phenomenon, a 2D large area coherent cavity can be constructed, and 2D lasing action can be realized. Fig. 3 shows the schematic structure of 2D photonic crystal laser. It is demonstrated that an unprecedented type of laser with a complete single longitudinal lateral, and polarization mode can be realized by this principle.



**Fig.3.** Schematic structure of 2D photonic crystal laser. Photonic crystals with square-lattice structure are integrated with the active layer. 2D distributed feedback phenomenon based on band-edge effect gives us a 2D cavity mode. Large area 2D coherent lasing oscillation becomes possible.

#### 4. Conclusion

It has been demonstrated that photonic crystals can offer various new ways of control of photons. Photonic nanostructure devices, photonic chips, novel lasers, etc, will soon become available. The worlds of photonic crystals are now expanding to various interdisciplinary areas such as bio-photonics, atom-physics, quantum computing and communications.

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