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, μ-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

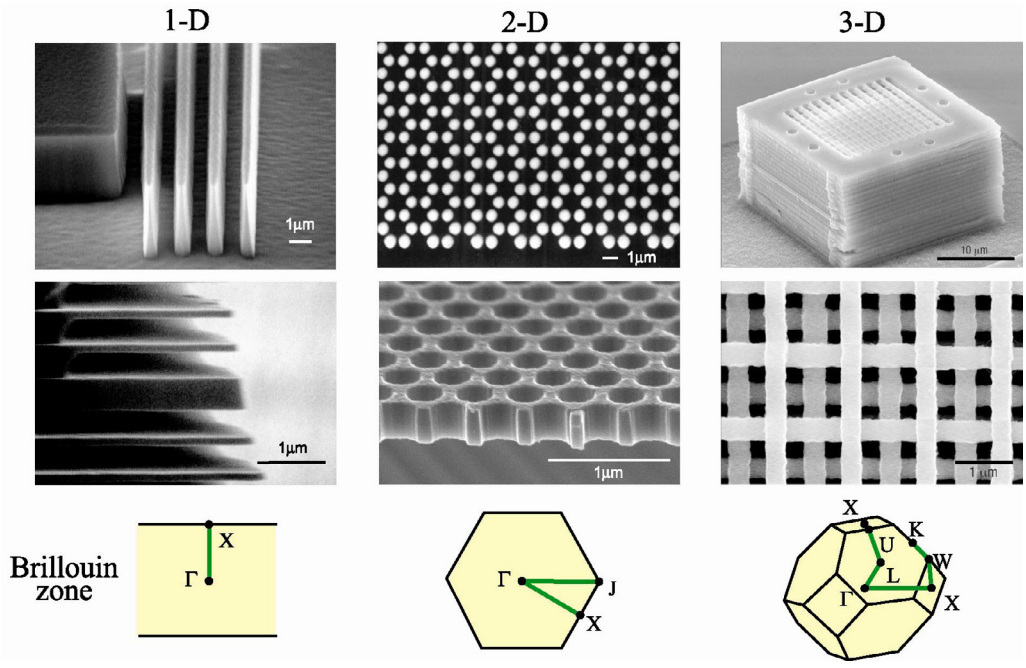

Fig. 1 Various photonic crystal structures of different dimensions and corresponding Brillouin zones.

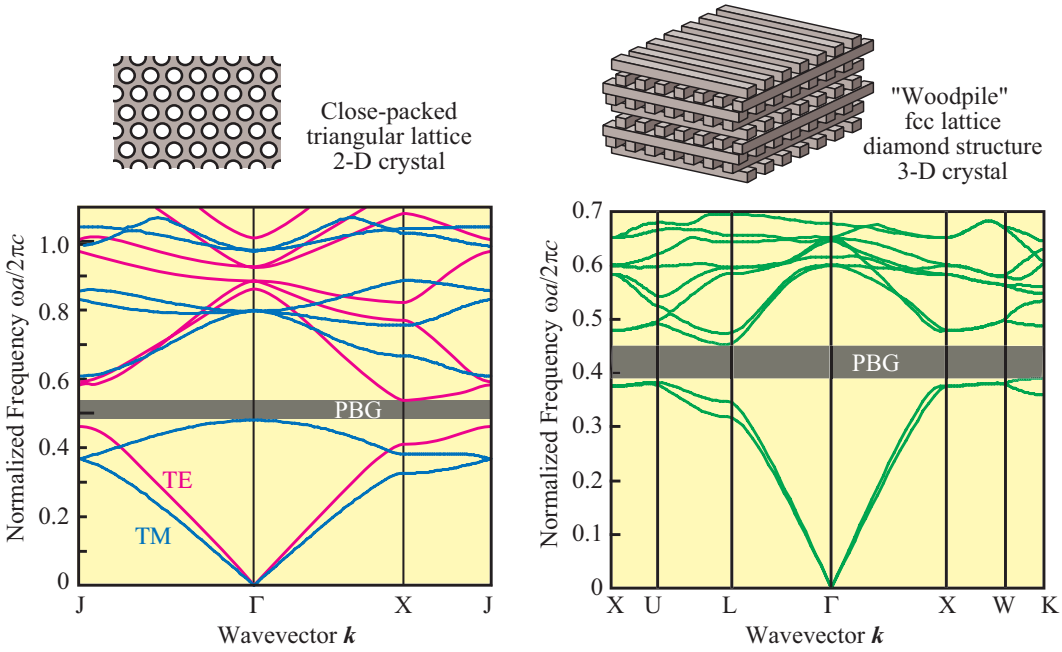

Fig. 2 Photonic bands of 2-D and 3-D photonic crystals.

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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