Tunability of Optical Properties of Photonic Crystal by External Force, Fields and Ambient Conditions

Katsumi YOSHINO

Department of Electronic Engineering, Graduate School of Engineering, Osaka University
Yamada-Oka 2-1, Suita, Osaka 565-0871 Japan
E-mail: yoshino@ele.eng.osaka-u.ac.jp

Recently photonic crystals with three-dimensional periodic structures of the order of optical wavelength have attracted much interest from both fundamental and practical view points, because novel concepts such as photonic band gap have been introduced and various exotic applications of photonic crystals have been proposed. The photonic band scheme such as a central wavelength and the width of photonic band gap depends on periodicity, crystal structure, filling factor, refractive indices of constituent materials.

We have proposed tunable photonic crystals. In tunable photonic crystals at least one of the above mentioned parameters which are determining factor of photonic crystal is controlled either by mechanical stress, electric field, magnetic field, light irradiation and ambient conditions such as gases and temperature.[1)]

As example of photonic crystal we prepared synthetic silica opals from SiO_2 spheres and also from polymer opals from polymer spheres such as polystyrene spheres of several hundred nm in diameter and replica opals.

By the sedimentation of mono-dispersed diameter of SiO_2 spheres, the synthetic silica opals were prepared. Utilizing polymer spheres, polymer opals can also be prepared by the sedimentation. These opals have interconnected periodic array of voids in which various materials can be infiltrated in either solution, gas phases or molten states. We gave demonstrated that various interesting properties evolve upon infiltration of functional materials in these voids.[2)]

Replicas of opals were also prepared by infiltrating various materials in the percolated periodic array of voids in the synthetic opals and then removing SiO_2 spheres by HF.

Here, we report some examples of tunable photonic crystals.

(a) Mechanical tunability

Periodicity and filling factor of the opals and infiltrated opals can be easily controlled by the applied mechanical stress. In the case of the silica opal by applying pressure we can observe change of the periodicity; reversible change in the stress bellow mechanical fatigue and irreversible large change in the pressure above fatigue, which results in the change of the optical properties such as photonic band gap.

In the case of polymer opals, especially opals prepared from elastomer spheres we demonstrated reversible change of optical properties such as the dip in the transmission and the peak in reflectance with changing relatively weak mechanical stress; compression and also elongation.[3)] The results can be well explained in terms of the change of the periodicity with mechanical stress.

(b) Electric field and Magnetic field tunability

When the properties of infiltrated materials or materials used for replica can be controlled by electric field or magnetic field, the photonic band schemes can also be controlled. For example, upon applying electric field or magnetic field reorientation of liquid crystal molecules in the pores induces the change of refractive index, resulting in the tuning of photonic properties[4)] Among various liquid crystals ferroelectric liquid crystals and anti-ferroelectric liquid crystals infiltrated in the voids of opals are highly promising, because field strength necessary to re-orient the molecular orientation of ferroelectric liquid crystal is much lower than in usual nematic liquid crystals in which anisotropy of dielectric constant plays role.

In the case of conducting polymer infiltrated opals upon electric field application in electrolyte solution doping progress electrochemically, which results in the change of optical properties and also photonic crystals.[5)]

In the case of magnetic field the reorientation of the liquid crystal molecules due to the anisotropy of diamagnetism can also be used for tuning of photonic crystals.

It should also be mentioned that the opals infiltrated with superconducting material also exhibit interesting characteristics. In this case, upon applying magnetic field above the critical magnetic field, the transition from the superconducting state to the normal conducting state takes places, resulting in the drastic change of properties with which the tunability of photonic crystal is also realized.

The opals infiltrated with magnetic fluids or magnetic liquid crystals can also exhibit the possibility of magnetic field tuning of photonic crystals.

(c) Optical tuning

Optical properties of materials infiltrated in the synthetic opals and also constitute opal replica can also be controlled by light irradiation. We have demonstrated that the optical property of photonic crystals infiltrated with photochromic molecules or polymers and polymers containing photochromic moeties such as azobenzene in the side chains can be controlled by the light irradiation. In this case, we can make either permanent or transient control of the photonic crystal by light irradiation.

Materials which exhibit photo-induced phase transition is also interesting material to be infiltrated in the synthetic opals.

(d) Temperature tunability

Optical properties of either opals infiltrated with temperature sensitive materials and also replicas made of such temperature-sensitive materials can exhibit temperature tunability. We have demonstrated such tunability utilizing opals infiltrated with liquid crystals and also with conducting polymers.[6] For example, utilizing thermo-chromic polymer such as poly(3-alkylthiophene) infiltrated in the voids of the opals, temperature tuning of photonic crystal have been demonstrated.[7]

It should also be mentioned that even in the case of silica opals, the tuning of optical properties as photonic crystals can also be realized by the heat treatment of high temperature (750C-950°C) ,that is, the fine tuning of the optical properties was realized due to the change of periodicity by sintering effects for such heat-treatment.

(e) Tuning by ambient gases and solvents

The optical properties of the photonic crystal can also be controlled by changing the ambient gases and also solvents. There gases and solvents can be infiltrated in the percolated nano-voids, which results in the large shift of the stop band due to the change of refractive index from those of air or vacuum.

It should also be mentioned that in replicas made of gas or solvent sensitive polymers, the large shift of the stop band was observed. In this case not only the change of refractive index from that of air to those of gases or solvents molecules but also the change of the periodicity also plays important role. In the last case, swelling of the replica polymers are observed, which results in the change of periodicity.[8)]

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