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Photonic Crystals with Graded Periodic Structure and Positional Tunability

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Recently photonic crystals with three-dimensional periodic structure of the order of optical wave length has attracted much attention from both fundamental and practical view points. We have prepared a synthetic opal as one example of photonic crystals by the sedimentation of SiO_2 spheres of several hundreds nm in diameter. Replicas of opals which are prepared by infiltrating various materials in the percolated periodic array of voids in the synthetic opal and then removing SiO_2 spheres by HF, also exhibit unique characteristics as photonic crystals. We have also demonstrated that synthetic opals and replica opals infiltrating with various functional materials, exhibit novel properties.

The optical properties of photonic crystal such as photonic band scheme (central wavelength and width of a photonic band gap) depends on the periodicity and refractive indices of constituents. In the preparation process of the synthetic opal by the sedimentation of SiO_2 spheres, mono-dispersed diameter of SiO_2 spheres have been used for the preparation of good quality of the sample.

Here I discuss the preparation of opals by the sedimentation of SiO_2 spheres of non-monodispersed diameters. For example, by the sedimentation of the mixture of the SiO_2 spheres of 180nm and 210nm in diameters, a graded structure of the opal can be prepared. Generally large spheres precipitate faster than the smaller spheres, because of the difference of weight. In this case at the bottom and lower part of the vessel spheres of 210nm precipitate and at the upper part of the vessel spheres of 160 nm precipitate. However, in the middle part both spheres are not completely separated and a little mixed. Therefore in this case we can realize a graded structure of opal. This graded structure of opal as photonic crystal behaves as two photonic crystals with different photonic band gaps in series, for the light penetrating in parallel to the graded direction. In some cases photonic band gap can overlap.

On the other hand, for the light coming perpendicular to the graded direction, the photonic band gap is different depending on the position from which the light beam is penetrating. In this case, positional tuning of photonic band gap can be realized, that is, by sliding the graded photonic crystal perpendicularly to the light beam.

Such graded structure of opals can be prepared by stacking two different opals made of different diameter of spheres, therefore with different periodicity, and then by heat-treatment at around 750°C-950°C. Then the sintering effect make the single photonic crystal with different periodic parts. At the interface between two parts of different spheres and therefore different periodicity, lattice mismatch can be formed. This local defects bring interesting effect in the photonic crystal. On the other hand, because of diffusion and fusing the graded structure can also be realized locally.

Graded structures of photonic crystals can also be prepared by the sedimentation of the mixture of SiO_2 spheres and plastic spheres. Even if their diameters were the same, their precipitation time is different, resulting in the graded structure of opals. The part of silica spheres has different photonic band gap from that in the polymer part, because the their refractive indices are different.

On the other hand, even in the case of single opal, by giving gradient in the properties of the material infiltrated in the nano-scale interconnected voids, graded structure of opals can be formed. In the case of uniform infiltration, either by the non-uniform light irradiation, non-uniform doping or non-uniform heat-treatment, we can make gradient in the property of the infiltrated material and therefore graded photonic crystals.