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Photonic crystals: a novel class of functional materials

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Photonic crystals are inhomogeneous materials whose dielectric properties vary periodically in space on a macroscopic scale. These materials have novel and interesting properties concerning both basic physics and technological applications. After a brief description of the main properties of photonic crystals, we present some specific applications related to wave guiding and Anderson localization of light due to stacking faults in these crystals.

Key words: *photonic crystals; optical wave guide; Anderson localization*

1. Introduction

Photonic crystals are composite materials whose dielectric properties vary periodically in space on a macroscopic scale [1–3]. For example, a photonic crystal may consist of non-overlapping dielectric or metallic spheres arranged periodically in a host medium with a different dielectric function. When the diameters of the spheres and the lattice constant are of the same order as the wavelength of light, we cannot describe the optical properties of the composite medium using an effective-medium approximation (this approximation holds when the wavelength of light is much larger than the lattice constant). Therefore, for a given photonic crystal (and a given lattice constant) we expect to see qualitatively new phenomena – different from those observed in a homogeneous medium – at sufficiently high frequencies of the electromagnetic (EM) field and when the wavelength of the EM waves is about the same or smaller than the lattice constant. At these frequencies, one expects to find phenomena that can be derived from the multiple scattering of light (we shall use the term light to stand for any EM wave in what follows) by a multitude of scatterers in the medium.

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Having in mind a photonic crystal of non-overlapping spheres in a host medium, we can state the basic problem related to the modes of propagation of light in the infinite crystal as follows. At a given frequency ω the wave scattered from a particular sphere of the crystal is generated by the wave incident on this sphere, which consists of the waves scattered by all other spheres in the crystal. Naturally, this leads to a homogeneous system of equations (essentially the Maxwell equations in some form), which may or may not have physical solutions at the given frequency, i.e. solutions remaining finite everywhere in the infinite crystal. It turns out, as expected, that these physical solutions are of the Bloch wave type, familiar from solid state physics. There, the Bloch waves are solutions of the Schrödinger field the electron sees in a periodic array of atoms. In the present case, the Bloch waves are EM waves in the composite medium under consideration. It turns out that there are regions of frequency over which propagating modes of the EM field cannot exist in the composite medium (an appropriate photonic crystal), in the same way that electron states cannot have energies in the gaps of the energy band structure of a crystalline solid.

2. A photonic crystal with an absolute gap

In Figure 1, we show an example of a frequency band structure of a three-dimensional photonic crystal, which exhibits an absolute frequency gap. It consists of non-overlapping spheres with a dielectric constant ε_s = 12.96 in air (ε = 1). The spheres are arranged as in a diamond crystal with a lattice constant a. We view the

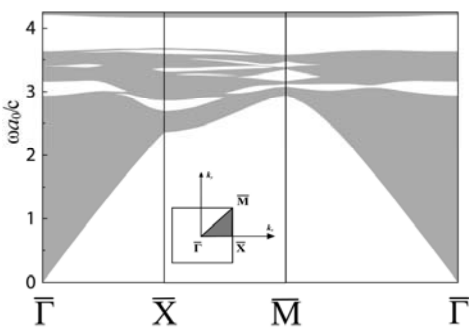

Fig. 1. Projection of the frequency band structure of a crystal consisting of dielectric spheres (ε_s = 12.96, S/a_0 = 0.25), arranged as in the structure of diamond in air (ε = 1), onto the SBZ of the (001) surface (shown in the inset)

crystal as a stack of layers parallel to the xy plane. The periodicity of the layers parallel to this plane is described by a two-dimensional square lattice defined by the primitive vectors $\mathbf{a}_1 = a_0(1,0,0)$ and $\mathbf{a}_2 = a_0(0,1,0)$, where $a_0 = a\sqrt{2}/2$ is the distance between second nearest neighbours in the diamond structure. A basis of two spheres with a radius of $S = a_0/4$, centred at (0,0,0) and $a_0(1/2,0,\sqrt{2}/4)$, defines the two planes of spheres of a layer. The (n+1)th layer along the z axis is obtained from the nth layer by a simple translation, described by the primitive vector $\mathbf{a}_3 = a_0(1/2, 1/2, \sqrt{2}/2)$. What Figure 1 actually shows, is the projection of the frequency band structure onto the surface Brillouin zone (SBZ) of the (001) surface of this crystal, in particular along the symmetry directions of the SBZ. For any value of $\mathbf{k}_{\|}$ (the reduced wave vector parallel to the (001) surface), the figure shows the regions of frequency over which at least one propagating mode of the EM field exists in the crystal (shaded regions) and those regions (gaps) where no such modes exist (blank regions). It is clear that an absolute frequency gap exists between $\omega a_0/c = 3.68$ and $\omega a_0/c = 4.16$ (c is the velocity of light in vacuum). We verified that this is indeed true by calculating the band structure at a sufficient number of $\mathbf{k}_{\|}$ points within the SBZ, using a layer multiple-scattering computer code [4, 5]. Over the region of an absolute frequency gap, there can be no propagating wave in the crystal in any direction of propagation, and a slab of the material (sufficiently thick) behaves like a perfect mirror for the light at all incidence angles. The technological applications of this property of photonic band gaps in the construction of useful devices in optoelectronics can be far-reaching. For example, a wave guide with walls made of such a material is an obvious possibility, and a lot of progress has already been made in this direction, especially in relation to two-dimensional wave guides [6].

3. Coupled resonator optical wave guides

A different type of wave guide, intrinsic to photonic crystals, which has come to be known as the coupled cavity wave guide (CCW) or coupled resonator optical wave guide (CROW), was suggested by us in 1998 [7] and, independently, by Yariv et al. a year later [8]. Imagine a photonic crystal with an absolute frequency gap, such as the one described in Figure 1. If we replace one of the spheres by a slightly different one

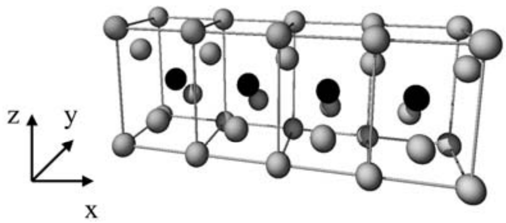

Fig. 2. A diamond structure of spheres. A linear chain of defect spheres (black spheres) is introduced along the [110] direction, which is taken as the *x* axis

(a defect sphere), we obtain a localized state of the EM field within and about this sphere at a frequency within the gap. In reality, one obtains a degenerate state, but for the sake of simplicity we shall assume that we have just one non-degenerate state. If a photon of this frequency is somehow generated within this sphere, it will stay there for ever in the absence of absorption. Now imagine a periodic chain of such spheres along a straight line, as shown in Figure 2. There is bound to be some coupling between these spheres (a hopping interaction). This leads to a one-dimensional narrow band of states, with a width depending on the strength of the coupling between the spheres. Light can now propagate along the chain with a (group) velocity much smaller than that in a homogeneous medium. This velocity can be, to some degree, adjusted to suit a number of purposes. It is also interesting to note that, under certain conditions, the chain can consist of a number of sections joining at angles, and light will still flow through it without being reflected at the corners, which is indeed remarkable and potentially very useful in the design of integrated optoelectronic systems. There is presently a lot of activity related to CCWs [9–16], and hopefully there will be interesting applications, too.

4. Anderson localization of light

We would like to close this short review with a brief reference to a quite different problem, which shows the richness of photonic crystals as an area of research. We have established that a random introduction of stacking faults in a slab of an inverted-opal photonic crystal leads to Anderson localization of light (localization due to disorder) over certain frequency regions around the absolute frequency gap [17, 18]. We show this by calculating the transmission coefficient of light incident on a slab of the material as a function of the thickness D of the slab. When Anderson localization occurs, the ensemble-averaged logarithm of the transmittance of the slab $\langle \ln T \rangle$ diminishes with thickness as $\langle \ln T \rangle = -2D/l$, which allows us to determine the localization length l at various frequencies of the incident light. Hopefully such systems can be built in the laboratory [19, 20] in which case the possibility arises to directly compare theory and experiment at a quantitative level, something that is indeed quite rare in studies of Anderson localization phenomena.

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