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(Invited)

Photonic Band Gap Materials

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Summary

It is now some time since Yablonovitch proposed the optical analogue of the electron band gap: periodically structured dielectrics may totally exclude light in certain frequency ranges. At the time this concept of a 'photonic insulator' provoked a furore and not a little disbelieve, but the concept is now an accepted one and the attention of the community is turning to how we can exploit the electron-photon analogy to control photons with the same facility as we do electrons. We may want to build better lasers, or to exploit more effectively use of light in communication, pushing the boundary of opto-electronics more in favour of the optical component of the subject.

Theory has contributed the greater part of the debate because of the difficulty of synthesising materials microstructured in three dimensions. However technologies for hole drilling on the micron scale are advancing rapidly and few would doubt that a micro- machining capability is not far off. Certainly biology abounds with examples of materials structured on exactly the scale for optical diffraction: peacocks' feathers and butterflies' wings are but two of the more sensational instances of diffraction effects due to natural microstructure. To my knowledge there is no naturally occurring example of a photonic band gap: a challenge for genetic engineering perhaps?

In the mean time theory provides us with some tantalising glimpses of what will become possible in the near future. We shall describe some of the theoretical approaches used including the specialist techniques needed to treat complex periodic structures. We shall give some examples of theoretical studies of photonic materials including an account of the scanning near field optical microscope for which we have developed a specially adapted version of the theory. Not only can this device be used to image a surface, but it can also change the lifetime of excited atoms exposed to the altered density of electromagnetic states near the scanning tip.

Another interesting aspect of photonic materials is the strongly modified electron-photon coupling they exhibit. This can be exploited particularly in semiconductor materials to modify the efficiency of lasers by enhancing or inhibiting chosen processes. One way of viewing the interaction is as a process of Cerenkov radiation: electrons in a semiconductor may travel faster than the very slow optical waves found at a band edge, and hence radiation can occur. This process competes with the conventional inter-band transition mechanism more familiar to us in unstructured semiconductors. Particularly dramatic modification of electron photon interaction is seen when the system has a metallic component and we shall spend part of the time discussing the impact that micro structured metals may have.

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OPTICAL TRANSMISSION OF PHOTONIC COLLOIDAL CRYSTALS.

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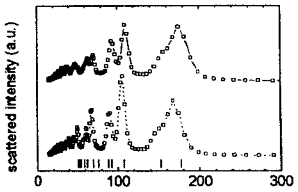
Currently, a great effort is put in making optical photonic crystals, i.e. 3D periodic composites of dielectric materials with a lattice parameter a of the order of visible wavelengths λ. This is driven by the goal to make optical band gaps, that are expected in suitable crystal structures for refractive index contrasts $m > 2$ [1], and photonic parameters - defined as the polarizibility per volume - $\Psi = 4\pi\alpha/v > 0.5$ [2].

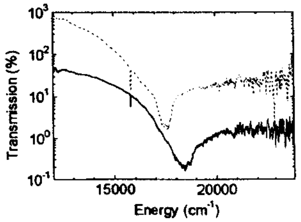
Colloidal suspensions consist of particles with radii r between ~1 and 1000 nm and thus naturally offer the correct length scales for optical experiments. Moreover they can spontaneously form colloidal crystals containing many unit cells. To interpret optical experiments on photonic colloidal crystals, it is essential to have information on the structure of the system. Optical diffraction or microscopy is hampered for two reasons: first, for large Ψ, the system is so multiply scattering that it becomes difficult to interpret diffraction experiments [2], and second, for band gaps in the visible spectrum the pertinent structural information shifts into the UV. Therefore, we have initiated small angle X-ray scattering (SAXS) experiments on the dedicated beamline 4 of the ESRF, France.

In Fig. 1 shows the SAXS pattern of a polycrystalline assembly of r=99 nm polystyrene particles suspended in methanol that were centrifuged to a volumefraction of about 50 %. Many Bragg peaks are seen, indicative of a high degree of ordering, and that can be indexed as f.c.c. peaks, but not as any of the other common colloidal structures. We note that optically, only the first peak can be measured, which would not allow structure identification. Patterns measured at different positions in the sample reveal that higher up the density is lower because the the Bragg peaks have shifted to larger spacings.

In Fig. 2 shows optical transmission parallel to the 111 axes of the crystals in the same sample, which has parameters m=1.19 and Ψ=0.2. Clear minima are seen at about 18000 cm^{-1} that are caused by the stopgap at the L point in the Brillouin zone [1]. The energy E of the gaps correspond very well with the measured Bragg spacings. It also explains the bright green reflectance of the samples. Finally, we note that if the width ΔE of the stop gaps is estimated at 'half depth', $\Delta E/E \sim 9.5$ % which is to our knowledge the largest optical stop gap in 3D photonic crystals to date.



SAXS diffraction pattern of a colloidal crystal as a function of diffraction angle θ, and λ=0.15 nm. Signal was ratiod to that of a dilute suspension.



Optical transmission of crystals at various heights in the sample corresponding to Fig. 2. The upper curve has been offset.

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2058 (1987); S. John, ibid. **58**, 2486 (1987). For an overview, see e.g.: eds. C.M. Bowden, J.S. Dowling, H.O. Everitt, J. Opt. Soc. Am. **B 10**, 280 (1993).
[2] W.L. Vos, R. Sprik, A. van Blaaderen, A. Imhof, A. Lagendijk, and G. Wegdam, in *Photonic Band Gap Materials*, ed. C. Soukoulis (Kluwer, Dordrecht, in press); Phys. Rev. B (submitted).