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Appearance of photonic minibands in disordered photonic crystals

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Abstract
We have demonstrated the appearance of photonic minibands within the photonic bandgaps of a disordered system represented by randomly distributed 'vacancies' of air cylinders. The positions of the photonic minibands are defined by the energies of the localized photonic states of the single defect, and their width increases with increase in the concentration of the defects. The appearance of the minibands makes possible the construction of spectral filters with thin transmission bands.

Photonic crystals promise a potentially wide range of applications in various areas of optoelectronics, such as lasers, waveguides, optical fibres, optical circuits etc [1–3]. However, apart from the difficulty of achieving a complete photonic band for all directions and light polarizations, the unresolved problem of fabrication-related disorder prevents the wide use of photonic crystals [4–9]. In two-dimensional photonic crystals obtained by etching air cylinders in dielectric material, disorder can occur as the roughness of the surface and variations of the hole radii. In self-assembled opaline [10] photonic crystals formed by spheres packed in a face-centred or hexagonal structure, the missing spheres in the crystalline lattice constitute another important kind of disorder. The aim of the present work is to investigate the influence of random or ordered configurations of such vacancies in a photonic crystalline lattice on its optical properties and density of modes. As a model system we consider a two-dimensional hexagonal photonic crystal, as illustrated in figure 1. The radius of the cylinders r is coupled to the distance between the centres of the cylinders as $r = 0.4d$. The symmetry points of the Brillouin zone of the hexagonal photonic crystal are shown in figure 1 and denoted by Γ, K and M. In this structure a *complete* photonic bandgap exists for the TE photonic modes in the frequency region from $fd/c = 0.24$ to 0.38, as shown in figure 2(a). The photonic bandgap is accompanied by a dip in the transmission spectrum [11] where light propagating through the structure experiences exponential decay, as shown in figure 3(a) by the dashed curve.

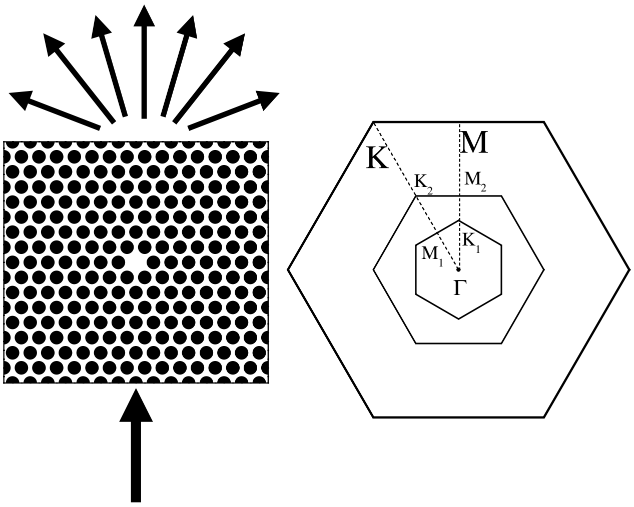

Figure 1. Schematic view of the supercell of a two-dimensional hexagonal photonic crystal with a single vacancy. The black circles correspond to air cylinders. Solid arrows indicate incident light and light transmitted in the same direction as the incident light. On the right the Brillouin zone of the ideal hexagonal structure with symmetry points (ΓKM), and also the photonic supercrystals PSC1 ($\Gamma K_1 M_1$) and PSC2 ($\Gamma K_2 M_2$) are shown.

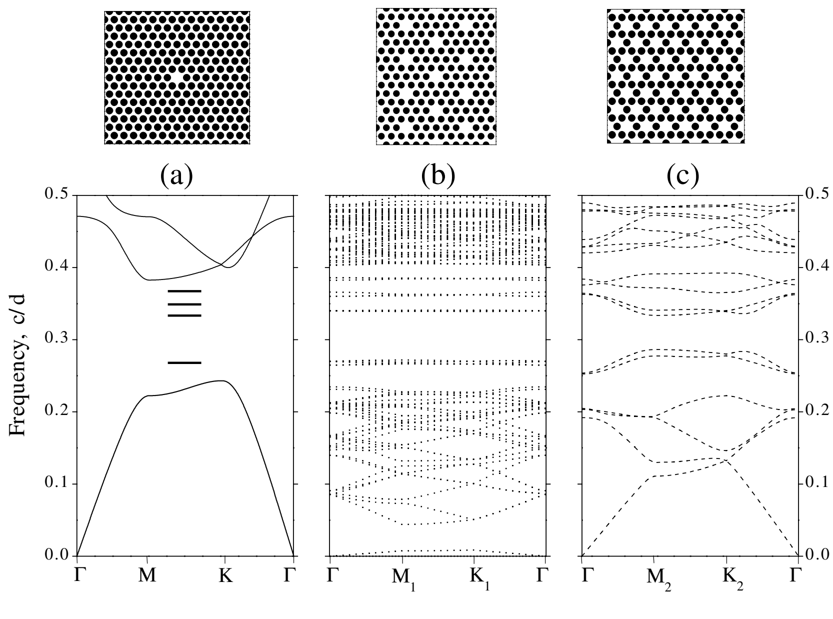

Figure 2. (a) Photonic band structure for TE polarization of the ideal (without disorder) hexagonal structure under study. Horizontal bars shows the energies of the photonic states localized on the individual vacancy shown above. (b) Band structure of the photonic supercrystal PSC1 shown above. (c) Band structure of the photonic supercrystal PSC2 shown above.

The introduction of defects into the photonic crystal leads to the localization of light. A vacancy in the photonic crystals induces discrete localized photonic states in the previously complete bandgap with corresponding sharp spikes in the transmission spectra, as shown

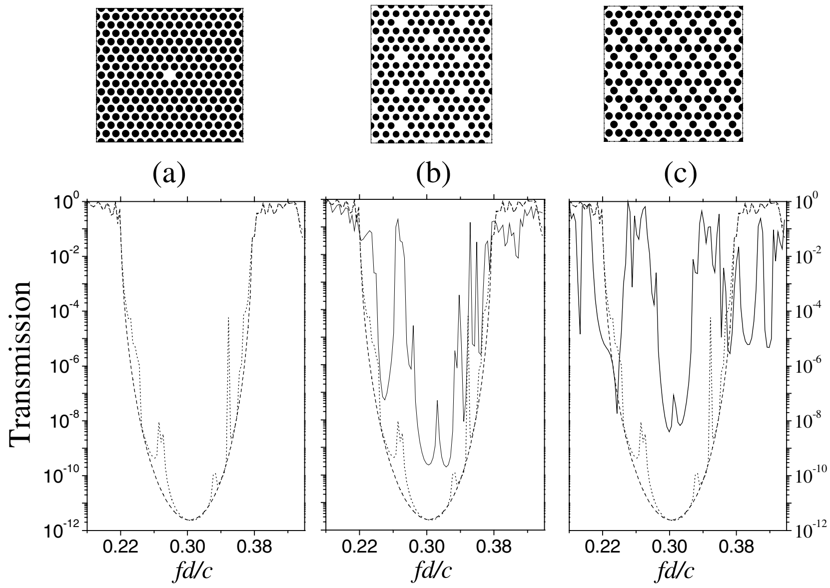

Figure 3. (a) Transmission spectra for the supercell with single a vacancy (dotted curve). (b) Transmission spectra for photonic supercrystal PSC1 (solid curve). (c) Transmission spectra for photonic supercrystal PSC2 (solid curve). The transmission spectra of the ideal structure (dashed curve) and supercell with the single vacancy (dotted curve) are shown on all figures for comparison.

in figures 2(a) and 3(a) (note that the highest-frequency localized state manifests itself as a shoulder on the right side of the spectral dip in figure 3(a), rather than a spike).

Photonic states localized on two separated defects can interact with each other, leading to a splitting of the original degenerate eigenmodes. The value of the splitting is proportional to the overlap of the localized photon eigenmodes of the two defects, which in the one-dimensional case of two coupled microcavities is proportional to the amplitude transmission coefficient of the Bragg mirror separating the two planar cavities [12]. In a chain of microcavities, the split states transform into a miniband, which can be considered as the photonic analogue of the electronic minibands of a semiconductor superlattice. The width of the minibands is proportional to the value of the splitting of two nearest-neighbour localized states.

In the two-dimensional case, an overlap of the localized photonic states could facilitate the propagation of photons by hopping. The line of vacancies (which can be curved or even zig-zag in shape) is known as a coupled cavity waveguide and has recently become the subject of numerous theoretical and experimental studies [13–15].

The periodic arrangements of vacancies in figures 2(b) and (c) (which we refer to as PSC1 and PSC2 respectively) are the two-dimensional analogues of a planar superlattice which we may call a photonic supercrystal (PSC).

Overlap of the localized photonic states induces minibands in what was a photonic bandgap in the original structure. For PSC1, where the concentration of the vacancies is relatively low at $1/12 \approx 8.3\%$, the distance between the vacancies is sufficiently large that the photonic states localized at these vacancies interact only weakly. Hence, the positions of the minibands correspond to the frequencies of the individual localized modes, and their widths are very small. However, the frequencies of the minibands are slightly shifted from the modes associated with the individual vacancy, which can be attributed to the modification of the averaged refractive index of the whole structure.

An interesting feature of PSC1 is that the directions of symmetry of the basic hexagonal structure and that of the lattice of defects are shifted by 30° relative to each other. Also the angular dispersion of the modes of PSC1 is reduced in comparison with the basic hexagonal structure. The minibands are accompanied by bands of increased light transmission within the dip corresponding to the photonic bandgap (PBG) as shown in figure 3(b). Note that the bands of increased transmission correspond to the peaks in transmission spectra of the photonic crystal with a single defect, shown in figure 3(a). It should also be noted that the transmission spectrum of PSC1 has several additional smaller spikes which do not correspond to minibands. These could be explained as being due to the surface modes [16, 17] of the PSC or to the interference of the Bloch modes of the PSC that are reflected from the front and back sides of the sample. Surface photonic states modify a transmission spectrum by introducing spikes into the spectral dips corresponding to the PBG. For example, for the hexagonal two-dimensional photonic crystal under study, in the case of uncut surface row cylinders a surface localized state appears near the centre of the PBG, and the frequency of such a state will strongly depend on the position of the front (rear) boundary of the structure, and will disappear when the boundary crosses the centres of the cylinders. Therefore, to avoid any influence of surface localized states on the optical spectrum of the system we cut the front and rear rows of cylinders.

If the density of defects is increased, as in structure PSC2 (the concentration of the vacancies is $1/4 \approx 25\%$), the width of the photonic minibands becomes larger. Further, the three upper minibands merge, as shown in figure 2(c). In the transmission spectra one can see two bands of increased transmission, where transmission is increased by a factor of 10^6 in comparison with the transmission of the initial hexagonal structure. It can also be seen that the transmission spectrum is punctuated by the spikes, which are either associated with the interference of the Bloch modes of the supercrystal or with the surface localization of such states.

Thus we can conclude that a periodic arrangement of vacancies leads to the formation of minibands in the photonic bandgap, and the position of the minibands is defined by the frequencies of the photonic states localized on a single vacancy. The width of the photonic minibands increases with increasing vacancy concentration.

A natural question then arises. How will the properties of the system be changed if the distribution of vacancies is random rather than periodic? Light transmission in such structures can be considered as a hopping of photons from one defect to another, and such hopping becomes more efficient with increasing vacancy concentration. Figure 4 shows the spectra of light transmission through the photonic crystal with randomly distributed vacancies with concentrations of (a) 2.9%, (b) 6.7% and (c) 8.3%.

The structures considered, along with their transmission spectra, are shown by the thin curves in the figures. It can be seen that the magnitudes of the transmission peaks and their widths are increased when the coupling between vacancies is enhanced. If the transmission spectra are averaged over different disorder configurations smoother, wider peaks are obtained. Comparing the enhancement of the light transmission for the structures shown in figures 3(b) and 4(c) (which have the same 8.3% vacancy concentrations) one can conclude that transmission of light by means of the Bloch states of PSC is more efficient than by hopping from one vacancy to another in the case of a random distribution of vacancies. We also note that for a random distribution there are no features in addition to those related to the isolated vacancy spikes.

By varying the parameters of the vacancy (for example by changing the neighbouring cylinder diameters) we can vary the number and frequency of the localized modes. On the

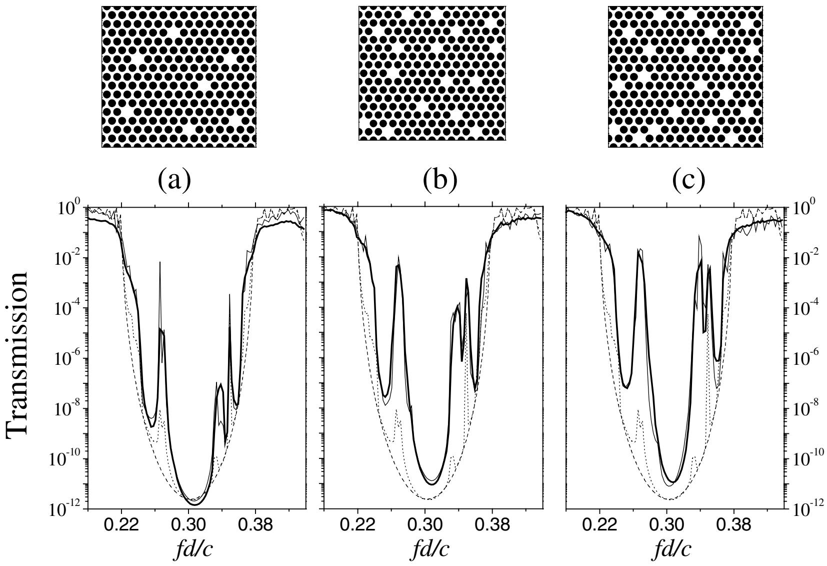

Figure 4. Structures and transmission spectra of the disordered photonic crystals with different concentration of vacancies: (a) 2.9%; (b) 6.7%; and (c) 8.3%.

other hand, by varying the concentration of defects, we can change the width of the minibands. Thus, we can in principle adjust the parameters of the photonic crystal in order to obtain, for example, a spectral filter with a predefined transparency band position and width.

To conclude, we have considered two-dimensional photonic crystals with defects in the form of either an ordered periodic (PSC) or a random distribution of vacancies. We have shown that in both cases photonic minibands appear in the former photonic bandgaps. The position of the minibands is defined by the energies of the photonic states localized on the individual vacancy, while the width of the minibands depends on the concentration of the vacancies. We propose that suitably engineered photonic microstructures of this type can be used to produce spectral filters.

Acknowledgments

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References

[1] Soukoulis C M 1993 *Photonic Bandgaps and Localization* (New York: Plenum)
[2] Burstein E and Weisbuch C 1995 *Confined Electrons and Photons: New Physics and Applications* (New York: Plenum)
[3] Joannopoulos J D, Meade R D and Winn J N 1995 *Photonic Crystals: Molding the Flow of Light* (Princeton, NJ: Princeton University Press)
[4] Meade R D, Rappe A M, Brommer K D, Joannopoulos J D and Alerhand O L 1993 *Phys. Rev.* B **48** 8434
[5] Ho K M, Chan C T and Soukoulis C M 1990 *Phys. Rev. Lett.* **65** 3152
[6] Genack A Z and Garcia N 1993 *J. Opt. Soc. Am.* B **10** 408
[7] Kaliteevski M A, Manzanares Martinez J, Cassagne D and Albert J P 2002 *Phys. Rev.* B **66** 113101

[8] Li Z Y and Zhang Z Q 2000 *Phys. Rev.* B **62** 1516
[9] Vlasov Yu A, Kaliteevski M A and Nikolaev V V 1999 *Phys. Rev.* B **60** 1555
[10] Vlasov Yu A, Astratov V N, Baryshev A V, Kaplyanskii A A, Karimov O Z and Limonov M F 2000 *Phys. Rev.* E **61** 5784
[11] Transmission calculations have been conducted using a modified version of the publicly available computer code of Bell *et al* see
Bell P M, Pendry J B, Moreno L M and Ward A J 1995 *Comput. Phys. Commun.* **85** 306
The band structure calculations were made using the plane wave method, see, for example
Plihal M and Maradudin A A 1991 *Phys. Rev.* B **44** 8565
[12] Kaliteevskii M A 1998 *Tech. Phys.* **43** 565
[13] Bayindir M, Temelkuran B and Obzay E 2000 *Phys. Rev. Lett.* **84** 2140
[14] Bayindir M, Temelkuran B and Obzay E 2000 *Phys. Rev.* B **61** R11856
[15] Lan S, Nishikawa S, Sugimoto Y, Ikeda N, Asakawa K and Ishikawa H 2002 *Phys. Rev.* B **65** 165208
[16] Meade R D, Brommer K D, Rappe A M and Joannopoulos J D 1991 *Phys. Rev.* B **44** 10961
[17] Ramos-Mendieta F and Halevi P 1999 *Phys. Rev.* B **59** 15112