Observation of total omnidirectional reflection from a one-dimensional dielectric lattice

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Abstract. We show that under certain conditions a one-dimensional dielectric lattice displays total omnidirectional reflection of incident light. The predictions are verified experimentally using a Na_3AlF_6/ZnSe multilayer structure developed by means of standard optical technology. The structure was found to have a reflection coefficient of more then 99% in the range of incident angles 0–86° at the wavelength of 632.8 nm for s-polarization. The results are likely to stimulate new experiments on photonic crystals and controlled spontaneous emission.

The concept of photonic crystals poses some challenging issues in modern condensed matter and optical science. Photonic crystals are periodic dielectric structures which offer the possibility of building up photon density of states in a similar way to electron density of states in conventional solids. Since the first pioneering works on this subject [1–3], much progress has been achieved in the calculation of photonic band structures of one- (1D), two- (2D), and three-dimensional (3D) photonic crystals and many novel applications in photonic devices have been proposed (see [4–6] and references therein). In particular, a complete 3D photonic band gap can be developed in a properly designed 3D photonic crystal. Spontaneous emission of atoms and molecules will be inhibited in such a crystal. A semi-infinite crystal will exhibit total omnidirectional reflection of incident light. These issues are of fundamental scientific and practical importance. For the optical range, within which the main applications are expected, most of experimental efforts have been concentrated on 2D and 3D photonic crystals [7–14]. However, to get a complete 3D photonic band gap one has to build a perfect 3D dielectric lattice with the refractive index contrast equal to 2 or even higher. This still remains a serious technological problem.

In this communication, we report that total omnidirectional reflection does not require a 2D or 3D photonic crystal [15]. We demonstrate theoretically and experimentally that under certain conditions a 1D photonic crystal can exhibit total reflection for all incident angles. A one-dimensional photonic crystal, which is nothing other than a familiar dielectric mirror consisting of alternating layers with low, n_1, and high, n_2, indices of refraction, is much easier to fabricate than a 3D one. Therefore the existence of total omnidirectional reflection in the case of a properly designed finite 1D dielectric lattice offers an alternative possibility to control the propagation of light.

When a plane electromagnetic wave propagates in a 1D periodic structure obliquely to the layer interfaces, only the normal component of the wave vector is involved in the band gap formation. The relative position of the band gap is shifted towards higher frequencies with the internal angle and the overall forbidden gap is always closed up. Due to the loss of the degeneracy between polarizations, the forbidden gaps do not coincide for the two fundamental polarizations. An obvious and common property of 1D periodic structures follows: there is no absolute nor complete 3D photonic band gap. In Fig. 1 the photonic band structure for a typical 1D photonic crystal with $n_1 = 1.2$, $\delta n = n_2/n_1 = 1.6$ and a filling fraction $\eta = d_2/d_1 = 1.0$ is shown in terms of the normalized frequency $\omega \Lambda/2\pi c$ and the internal angle in the low index layer. Here d_1, d_2, $\Lambda = d_1 + d_2$, ω and c are the thicknesses of the layers, the period of the structure, the frequency and the speed of light in vacuum, respectively. The band structure has been calculated using the analytical form of the dispersion equation (see e.g. [16]). The overall forbidden gaps are closed up both for s- and p-polarizations (Fig. 1). The internal angles for which the forbidden gaps are closed up are depicted by the vertical dotted lines. However, when an electromagnetic wave illuminates the boundary of the semi-infinite 1D photonic crystal, the possible values of the internal angles are restricted by Snell's law. The higher the refractive indices of
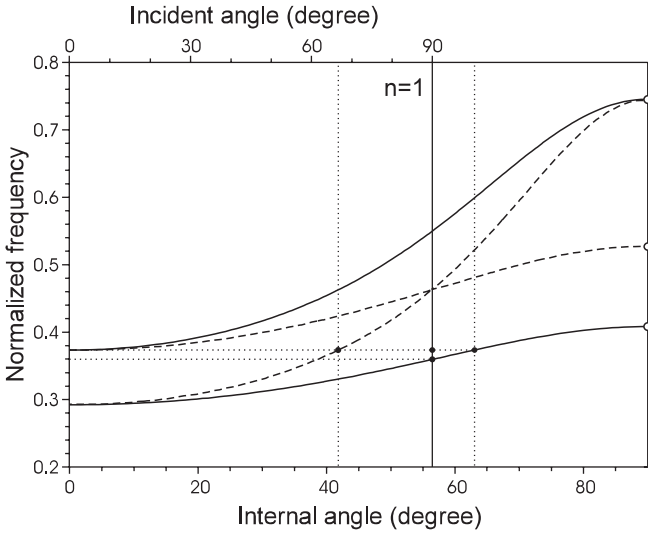
Fig. 1. Photonic band structure of a typical 1D photonic crystal in terms of normalized frequency $\omega\Lambda/2\pi c$ and the internal angle in the low index layer. The *solid* (*dashed*) *curves* are for s- (p-) polarization bands. Here, $n_1 = 1.2$, $\delta n = 1.6$ and $\eta = 1.0$

Fig. 2. Photonic band gap structure of semi-infinite periodic Na_3AlF_6/ZnSe lattice in terms of wavelength and incident angle. The *solid* (*dashed*) *curves* are for s- (p-) polarization bands. The grey area is the absolute omnidirectional band gap

the layers with respect to the medium outside the crystal, the narrower is the cone of internal angles. The solid line in Fig. 1 corresponds to the maximum internal angle in the case of an ambient medium with refractive index $n = 1$. For the structure presented (Fig. 1) an overall forbidden gap is opened for all incident angles in the case of an s-polarized wave and within an angular aperture of about $\pm 60°$ in the case of a p-polarized wave. Due to the Brewster effect at the interface of low and high index layers, the forbidden gap is always narrower and closed up at smaller internal angle for a p-polarized wave than for an s-polarized one. If the index of refraction of the ambient medium is smaller than $n_1 \sin \alpha_B$, which corresponds to the Brewster angle α_B at the interface of low and high index layers, and the index contrast in the layers is sufficiently large, the overall forbidden gap can be opened for all incident angles for both s- and p-polarized radiation. No propagating modes are allowed in the photonic crystal for any propagating mode in the ambient medium within such a forbidden gap and hence the total omnidirectional reflection arises. The detailed analysis of the conditions needed to obtain an absolute omnidirectional total reflection with 1D photonic crystals will be published in forthcoming paper [17].

To verify the predictions, we fabricated a lattice consisting of 19 layers of Na_3AlF_6 ($n_1 = 1.34$ in a wide spectral range within the visible) and ZnSe ($n_2 = 2.5$–2.8 in the visible range). The thickness of each layer was $d_1 = d_2 = 90$ nm and the period of the lattice $d_1 + d_2 = 180$ nm. The calculated photonic band structure of the lattice is presented in Fig. 2 in terms of wavelength and incident angle. The absolute omnidirectional photonic band gap exists in the spectral range 604.3–638.4 nm (the grey area in Fig. 2). The gap to midgap ratio is about 5.5%. The calculated transmission spectra for s- and p-polarizations at different incident angles are depicted in Fig. 3. There are clear overlapping stopbands for both fundamental polarization at any given incident angle, that is, total reflection occurs within a wide angular aperture. For calculations of the spectra we used the characteristic matrix method [18].
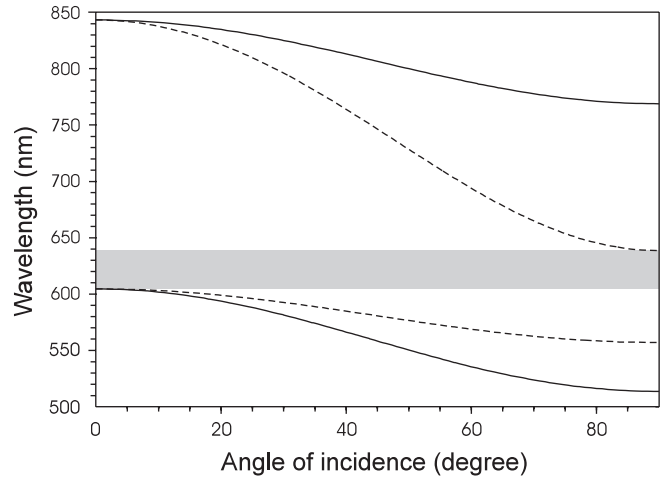
Transmission spectra for s- and p- polarizations at different incident angles in the range of 0–$60°$ were measured using a 'Cary 500' spectrophotometer (Fig. 4). A good

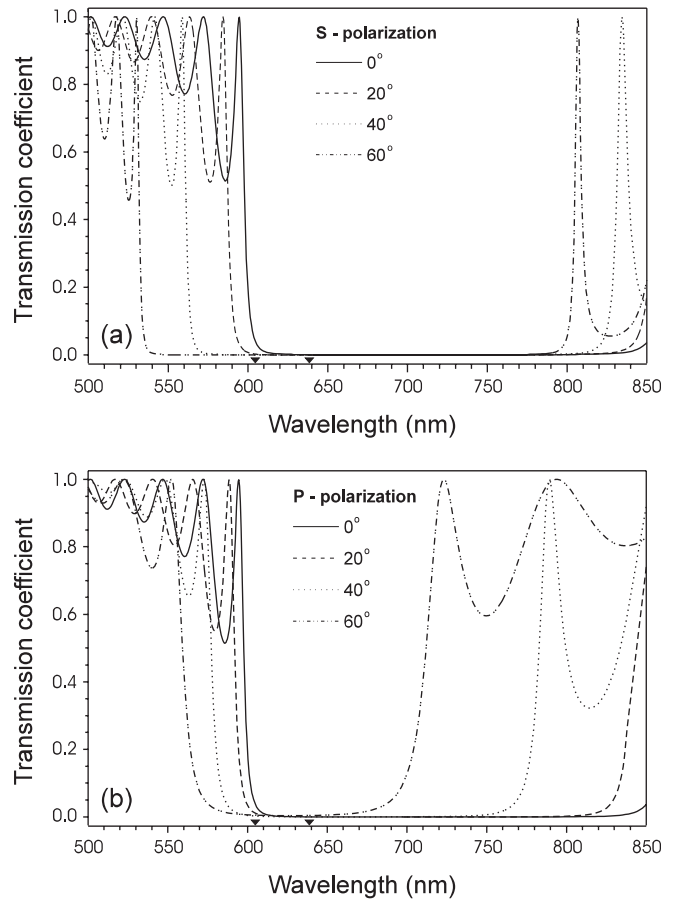**Fig. 3a,b.** Calculated transmission spectra of Na_3AlF_6/ZnSe 19-layer structure for s-polarized (**a**) and p-polarized (**b**) light at different angles of incidence ($0°$ – *solid line*, $20°$ – *dashed line*, $40°$ – *dotted line*, $60°$ – *dash-dotted line*). The lower triangles indicate the edges of the absolute omnidirectional band gap

agreement with theoretically predicted spectra is obtained. From Fig. 4 one can see that for spectral range 600–700 nm the transmission coefficient is very low for both polarizations even at 60°. The absolute values of transmission for s-polarization in spectral range 630–700 nm was less than 0.001 within the $\pm 60°$ aperture, corresponding to a reflection coefficient of 99.9%. To examine the transmission of this structure more precisely in a wider angular range, a simple set-up consisting of a HeNe laser and a CCD detector was used. This set-up allows one to directly determine the transmission coefficient of samples at angles up to 70°. For larger angles we have to measure the reflection coefficient of samples. The dependence of the transmission coefficients for the structure investigated for s- and p-polarized incident radiation of a HeNe laser at 632.8 nm upon angle of incidence is presented in Fig. 5. For p-polarization circles mark the directly measured transmission coefficient, and squares mark data obtained from reflection measurements. Mismatch between them can be attributed to additional reflection from substrate–air and air–ZnSe interfaces. The solid (dashed) curve in Fig. 5 gives theoretically calculated transmission coefficients for s- (p-) polarized light; a reasonable agreement with experiment is obtained. As can be seen from Fig. 5 the transmission coefficient of p-polarized radiation remains below 2×10^{-3} over a wide angular range. Due to the Brewster effect at the air–
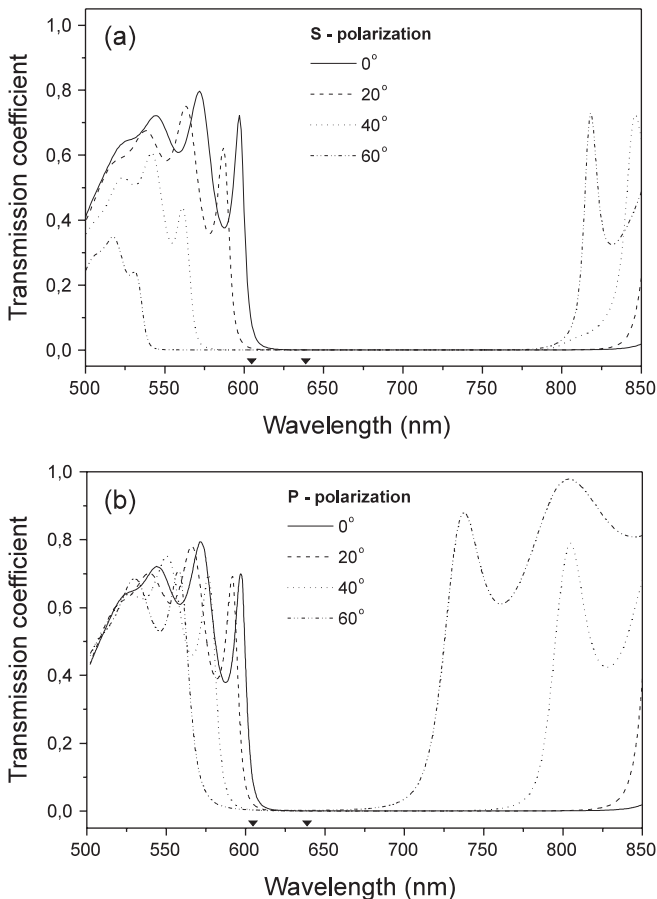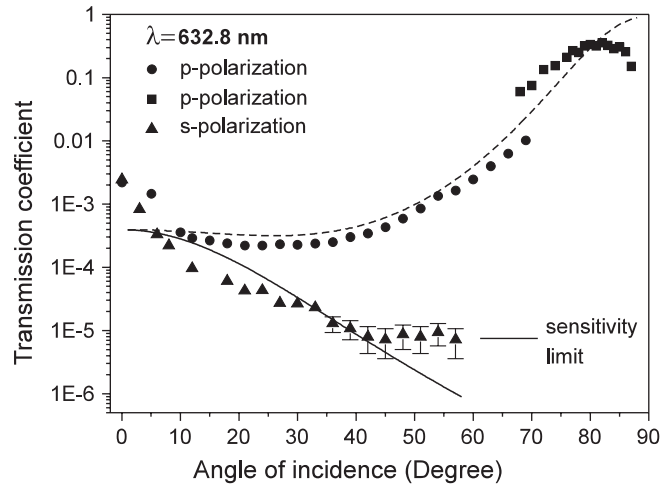

Fig. 5. Dependence of transmission coefficient of $Na_3AlF_6/ZnSe$ structure upon angles of incidence at wavelength of 632.8 nm (HeNe laser) for two polarizations of incident light. For p-polarization *circles* are directly measured transmission coefficients, *squares* depict transmission coefficients calculated from reflection measurement data. For s-polarization (*upper triangles*) the signal at angles more than 60° is out of the sensitivity range of the experimental set-up. The *solid* (*dashed*) *curve* is the theoretically calculated transmission coefficient for s- (p-) polarized light

ZnSe interface at large angles it increases to 0.33 at 80° and then decreases again. In contrast, transmission of s-polarized radiation decreases monotonically with growing angle of incidence (Fig. 5). Transmission coefficients of less than 10^{-5} are beyond the capabilities of the experimental set-up used. For this reason, the transmitted signal at more than 60° cannot be detected. Because of this, no data points for s-polarization at these angles are presented in Fig. 5.

To summarize, at 632.8 nm the examined structure exhibits a reflection coefficient for s-polarization of more than 99.5% in the angular range $\pm 86°$. A wider angular aperture is beyond the capability of our set-up. However, there is no doubt that reflection also remains very high outside the examined angular range. With respect to p-polarization, the reflectivity can be enhanced in structures with larger numbers of layers.

In conclusion, we have shown theoretically and experimentally that a one-dimensional dielectric structure can exhibit total omnidirectional reflection of incident light. Such a structure can be developed by means of standard fabrication techniques which are routinely used in the optical industry. These findings should stimulate new experiments on controllable spontaneous emission of atoms, molecules and solid state micro-structures in the optical range [19].

Fig. 4a,b. Transmission spectra of $Na_3AlF_6/ZnSe$ 19-layer structure measured for s-polarized (**a**) and p-polarized (**b**) light at different angles of incidence (0° – *solid line*, 20° – *dashed line*, 40° – *dotted line*, 60° – *dash-dotted line*). The lower triangles indicate the edges of the absolute omnidirectional band gap

References

1. V.P. Bykov: JETP **62**, 505 (1972)
2. E. Yablonovitch: Phys. Rev. Lett. **58**, 2059 (1987)
3. S. John: Phys. Rev. Lett. **58**, 2486 (1987)
4. J.D. Joannopoulos, R.D. Meade, J.N. Winn: *Photonic Crystals: molding the flow of light* (Princeton University Press, Princeton 1995)
5. J. Pendry: J. Mod. Opt. **41**, 209 (1994)
6. J. Haus: J. Mod. Opt. **41**, 198 (1994)

7. V.N. Bogomolov, S.V. Gaponenko, A.M. Kapitonov, A.V. Prokofiev, A.N. Ponyavina, N.I. Silvanovich, S.M. Samoilovich: Appl. Phys. A **63**, 613 (1996)
8. V.N. Bogomolov, S.V. Gaponenko, I.N. Germanenko, A.M. Kapitonov, E.P. Petrov, N.V. Gaponenko, A.V. Prokofiev, A.N. Ponyavina, N.I. Silvanovich, S.M. Samoilovich: Phys. Rev. E **55**, 7619 (1997)
9. E.P. Petrov, V.N. Bogomolov, I.I. Kalosha, S.V. Gaponenko: Phys. Rev. Lett. **81**, 77 (1998)
10. S.V. Gaponenko, A.M. Kapitonov, V.N. Bogomolov, A.V. Prokofiev, A. Eychmueller, A. Rogach: JETP Lett. **68**, 142 (1998)
11. M.C. Wanke, O. Lehmann, K. Müller, Q. Wen, M. Stuke: Science **275**, 1284 (1997)
12. J.E.G.J. Wijnhoven, W.L. Vos: Science **281**, 802 (1998)
13. R. Mayoral, J. Requena, J.S. Moya, C. Lopez, A. Cintas, H. Migues, F. Meseguer, L. Vazquez, M. Holgado, A. Blanco: Adv. Mater. **9**, 257 (1997)
14. R.C. Tyan, P.C. Sun, A. Scherer, Y. Fainman: Opt. Lett. **21**, 761 (1996)
15. D.N. Chigrin, A.V. Lavrinenko: In *Technical Digest of the 1998 OSA Annual Meeting and Exhibit* (Baltimor, Maryland, USA 1998) p. 118
16. P. Yeh: *Optical Waves in Layered Media* (Wiley, New York 1988)
17. D.N. Chigrin, A.V. Lavrinenko: Phys. Rev. Lett. (in press)
18. M. Born, E. Wolf: *Principles of Optics* (Pergamon, New York 1980)
19. When the manuscript of the present paper has been completed, a theoretical paper by J. Winn, Y. Fink, S. Fan, J.D. Joannopulos was issued (Opt. Lett. **23**, 1573, October 15, 1998) which contains basically the same idea but without experimental verification