Extending omnidirectional reflection bands in one-dimensional photonic crystals

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Abstract

The presence of the Brewster point in one-dimensional photonic crystals restricts the possibility of achieving full omni-directional reflection at large incident wave vectors. We show that it is possible to achieve omnidirectional reflection in both rarefied and refracting incident media utilising periodic structures consisting of three or more distinct layers with differing refractive indices. In these ternary periodic structures the Brewster condition is not satisfied simultaneously at all interface and so strong reflection bands are achievable at any angle of incidence and polarisation state. Combining the ternary structure with layer chirping is necessary to open the full omnidirectional band.

One-dimensional photonic band-gap structures with sufficiently large refractive index modulation have the possibility of achieving strong reflection at all incident angles and polarisation states within a specified spectral bandwidth [1]. Such features, known as omnidirectional reflection (ODR) bands, provide a quasi-full photonic band-gap for planar geometries where light has a restricted range of possible incident wavevectors, defined by the incident medium light cone. ODR mirrors have a significant advantage over their metallic counterparts in that they can achieve higher reflectances and negligible absorption losses within a defined spectral region [2]. As such, omnidirectional reflection has found significant uses in light guiding applications for a numbers of geometries where traditional methods are challenging [3].

Research in the area of omnidirectional reflectors has focused primarily on two aspects: (i) identifying material systems and fabrication methods that have the required dielectric contrast to achieve omnidirectional reflection for specific applications [4–6], and (ii) developing optical strategies that can be used to extend the ODR band for broad band applications.

For a given incident medium, the spectral width of the ODR band in a Bragg mirror is primarily determined by the refractive index contrast, \( \Delta n = n_b - n_l \) between adjacent layers and the average refractive index of the total structure, \( \bar{n} \). These parameters determine the respective full width of the reflection band at normal incidence and the degree of band bending at larger propagation constants [1]. Enlargement of the ODR band to spectral widths exceeding several hundred nanometers can be achieved using chirped structures where the optical thickness of the layers is varied as a function of the period number [7]; comparable results can also be achieved using stacked mirrors structures with a sequence of stacked mirrors covering adjacent spectral windows [8], and more complex chirping strategies [9, 10]. Omnidirectional band-gaps have also been demonstrated in graded periodic stacks [11, 12], as well as in hybrid structures consisting of multiple graded binary and ternary photonic crystals [13]. Other work has included the use of photonic structures with self-similar periodicities to create multiple ODR bands [14].

The presence of the Brewster point in the band diagram ultimately restricts the extension of ODR bands to high refractive index incident media. This feature corresponds to the propagation angle, \( \theta_B = \tan^{-1}(n_l/n_b) \), at which the forward and backward propagating waves become decoupled and light can travels unimpeded through the photonic crystal. The presence of Brewster point within the incident light cone makes achieving an ODR bandgap within that structure impossible. As \( \theta_B \) is only dependent on the refractive index of the composite layers; the bandgap closing cannot be obviated through layer chirping. For applications where the incident medium is refractive (e.g. water, glass etc.) the light cone is enlarged and it becomes impracticable to exclude the Brewster point using standard optical materials that are available through thin-film coating technologies.
In this letter we propose a method for eliminating Brewster point using a periodic structures consisting of three distinct dielectric layers. The inclusion of the additional layers introduces multiple Brewster conditions for the different dielectric interfaces, which are not simultaneously satisfied by a single incident wavevector. We experimentally verify the presence of reflection bands at Brewster points using porous silicon Bragg reflectors consisting of three different porous layers. A consequence of this approach is that it will reduce the average refractive index contrast within the structure, leading to a narrowing of the omnidirectional reflection band. Chirping the periodicity of the structure can be utilised to counter these effect. This demonstration opens many avenues for implementing ODR technologies in new areas of application, including integrated photonics, photovoltaics and optoelectronics.

In figure 1 we present a comparison of the band diagrams for a conventional Bragg reflector based on a quarter wavelength stack (Figure 1(a)) and a ternary layered structure (figure 1(b)) where a layer with an intermediate refractive index layer is included between the high and low regions. A schematic diagram of the layering profile for each structure is provided in figure 1(c). In the band diagrams, the regions in black correspond to propagating Bloch modes while white regions represent forbidden modes. Also included in each plot is the light line for an incident medium of air (dotted red) and water (solid blue). Band calculations are based on the dispersion relation for Bloch waves in a periodic structure

\[
K(\beta, \omega) = \frac{1}{A} \cos^{-1}\left(\frac{1}{2}(A + D)\right)
\]

where \(K\) is the Bloch wave number, \(\beta\) is the parallel component of the wavevector, \(A\) is the period, and \(A\) and \(D\) are matrix elements in the unit cell translation matrix. For \(\left|\frac{1}{2}(A + D)\right| < 1\), \(K\) is real and it represents a propagating Bloch mode. The refractive index values used in the calculations, \(n_1 = 1.4, n_b = 2.6\) and \(n_i = 2.0\). From figure 1 we observe that both structures support an ODR band for the case of air incidence. This is indicated by a range of frequencies where no propagation modes are present between within the cone defined by the light line. In particular, the three-layered structure has a narrower ODR band as the effective refractive index contrast between the three regions has been reduced. In figure 1(a) the Brewster point is clearly visible in the TM region where the upper air band meets the lower dielectric band. In the case of the three-layer structure the Brewster point is missing. This is caused by the fact that Brewster angle varies for different dielectric interfaces.

\(\text{Figure 1.} (a)\) Projected band structure for a conventional quarter wave Bragg reflector with \(n_l = 1.34\) and \(n_b = 2.61\). Dotted (red) lines indicate the light line for air medium of incidence; solid (blue) lines indicate the light line for glass medium of incidence. Brewster point can be seen in the TM part of the diagram. (b) Projected band structure for ternary structure with \(n_l = 1.34, n_i = 2.00\) and \(n_b = 2.61\) and corresponding light lines for air and water incidence. (c) Diagrammatic representation of the periodic structures for the two cases.
and as such, there is no one incident wavevector that completely eliminates reflections within the structure. In considering the case of the enlarged light-cone of (e.g. for a water incident medium) we see that, for the TM modes, significant band bending at large wavevectors and a closing of the band-gap reduces the size of the ODR band. Many strategies for enlarging the band-gap has been suggested, for instance, the introduction of an aperiodic thickness profile can overcome issues associated bending and narrowing. The absence of the Brewster point in the ternary structure in principle allows chirping strategies to achieve ODR bands for a wider range of incident media.

In order to validate the absence of the Brewster point experimentally, we perform spectrally and polarisation resolved angular dependent reflectivity measurements on mesoporous silicon multi-layered structures. These samples are prepared by anodic etching of 5 mΩ·cm, boron-doped, Cz-grown p+ Si wafers (Silicon Quest) under galvanostatic conditions in an ethanolic etching solution containing 25% HF acid. Different etching currents are used to control the porosity of individual layers whilst the etching time is used to determine layer thicknesses. Constant etching currents of 5 mA, 50 mA and 400 mA are used to produce layers corresponding to the high, intermediate and low refractive index layers. For this study, we fabricate two structures; a conventional Bragg reflector consisting of high and low refractive index layers; and a ternary structure that includes an additional intermediate porosity layer. Normal incidence optical reflectance measurements are used for optical characterisation and are modelled using matrix transfer method. The optical constants of each layer are related to the porosity by a two-part Bruggemann effective medium approximation model. In this case the porosities are estimated to be 38%, 51% and 78%. In order to align the spectral position of the high reflectivity bands of the ternary and bilayer structure at normal incidence, the thicknesses of the high and intermediate porosities layers are reduced in the ternary structures. In the binary structure the thicknesses for the high and low porosity layers corresponds to 235 nm and 100 nm respectively. The ternary structures consists of 117 nm, 75 nm and 100 nm for the respective high, intermediate and low porosity layers.

In figure 2, a cross-section scanning electron micrograph image it provided for the three layer structure. The structure consists of 30 periods of alternating low, intermediate and high porosity layers. Images were recorded with a FEI Nova NanoSEM in immersion mode with a 5 kV accelerating voltage and 3 nm spot size. The inset shows a high magnification image of the layers where the three different pore morphologies are apparent.

In order to access the large incident wavevectors required to probe the Brewster point, the photonic structures are mounted on a 25.4 mm hemispherical lens (fused silica, ISP Optics) using immersion oil for index matching. In order to avoid ingress of the oil into the porous structures, a thin layer of polymethyl methacrylate (MicroChem, PMMA) is deposited via spin-coating. Normal incidence optical reflectance measurements are used to verify that the PMMA formed a thin encapsulation layer without modifying the underlying structure. Polarisation-resolved, angular-dependent reflectance measurements were performed with the aide of a tablespectrometer rotation stage and a compact USB spectrometer (Ocean Optics, USB4000). Briefly, light from a fibre-coupled white light source is focused onto the sample with a 10 cm focal length planar-convex lens. The reflected light is collimated by collection optics before passing through a broadband polarising beamsplitter (CVI Optics, PBSH) and coupled to the compact spectrometer. The angle of incidence is set by rotating both the incident light and sample orientation with respect to the collection optics.

In figure 3(a), the measured and simulated reflectance spectra for the binary structure is presented for the TM-polarisation at a number of different angles of incidence, together with the normal incidence measurements.
in the top panel. The TE-polarisation (not presented) follows the expected trend of increasing monotonically with angle of incidence. As the angle of incidence is increased the TM-reflectivity band shifts to shorter wavelengths and reduces, as expected from the band-diagram at large incident wavevectors. At 56°, which corresponds to the Brewster point in this structure, the high reflectivity band is completely suppressed. By contrast, similar reflectance spectra for the ternary structure, shown in figure 3(b), shows no suppression at the Brewster angle (≈56°), whilst the ternary structure shows strong reflectivity bands at all angles of incidence. Note that the normal incidence reflectance was measured over an extended wavelength range to capture the full extent of the band-gap and was used for simulating the optical structure.

Figure 3. Measured (green/red) and simulated (blue) reflectance spectra for TM-polarised light for incident angles around near the Brewster point and at normal incidence. The column on the left corresponds to the binary structures with two distinct porous region. The right column corresponds to the ternary structure. In the binary structure, the high reflectivity band is suppressed at the Brewster angle (≈56°), whilst the ternary structure shows strong reflectivity bands at all angles of incidence. Note that the normal incidence reflectance was measured over an extended wavelength range to capture the full extent of the band-gap and was used for simulating the optical structure.
band-gap for both polarisation to achieve ODR bands. As an example, figure 4 shows the simulation of three-layer structure with $n_l = 1.34$, $n_i = 2.00$ and $n_h = 2.61$ and chirping of 90% (i.e. the last period is 90% thicker than the first one) over 90 periods. This structure exhibits an ODR band of approximately 200 nm. These optical constants are chosen to match the refractive index of the porous layers used in this study, however larger refractive index contrast could be used to achieve an ODR band with reduced chirping.

The realisation of the simulated structure in figure 4 is currently limited by technical challenges associated with porous silicon fabrication. Specifically, the requirement for large number of periods and the need for a high porosity region to achieve the requisite strong dielectric contrast leads to structural instabilities in the film. These issues may be overcome using advanced processing steps such as super-critical drying, however it is more likely that an alternate fabrication technique (e.g. evaporative deposition) would be more suited to demonstrate the full potential of the approach. For a more practical structure we have fabricated a chirped ternary structure with 40 periods and a thickness chirping of 70%. The reflectance of this structure has been presented in figure 5. In this figure, we see that spectral overlap of the high reflectivity band exists up to 65°, which is equivalent to a full ODR band for an incident refractive index of water. We note that the maximum reflectivity of the stop-band around the Brewster angle is distorted, which is expected from simulation and is due to the reduced number of periods used in the practical implementation.

The implications for this demonstration are that it has the potential to achieve lossless guiding and reflection in fluidic and glass media under a wider range of propagation angles. Currently guiding in planar devices is achieved through total internal reflection—however guiding using ODR mirrors can lead to slow light propagation modes that can enhance light-material interactions. It may also be possible to use ODR mirrors as a cladding layers for low contrast 2D-photic crystal waveguides. Other application may include planar photovoltaic and photo-thermal devices where photon losses in specific spectral band need to be minimised for enhanced device performance. For example, the use of an all-dielectric ODRs as a rear reflector in high efficiency solar cells may be useful in circumvent parasitic optical losses at long wavelengths associated with metallic rear reflectors [16]. In a further example, suppressing the photon density of states in spectral region around the band-edge (using an ODR) can potentially be used to suppress intrinsic optical loss associated with radiative recombination of photo-generated carriers in high efficiency solar cells [17]. Further applications may also include improving the performance of luminescent solar concentrators [18].

In conclusion, we have demonstrated a strategy for eliminating the Brewster point in a Bragg reflector by adding an additional intermediate refractive index layer between the high and low refractive index layers. This was verified using a three-layer porous silicon photonic structure. Removing the Brewster point can potentially
expand the use of omnidirectional reflection bands to include other incidence media than air, e.g. water or glass, with wide-reaching applications.

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