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Etched Bragg reflectors as two-dimensional photonic crystals

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Abstract

We have studied GaAs/oxidized AlAs (AlOx) Bragg reflectors with etched air grooves running parallel to the growth direction. Such structures possess periodic modulation of the refractive index in two dimensions, and we have found that they have a photonic band gap for E-polarized modes over a large range of parameters of the structure, and can support complete photonic band-gaps for both E- and H-polarizations for a more restricted range of values of the parameters. Also, for certain parameter values of the etched Bragg reflector, the total density of states in a wide spectral region is reduced by factor of up to 20 compared to an effective medium characterized by the mean dielectric constant.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Photonic crystals [1] are structures that possess a periodic modulation of the refractive index in one, two or three dimensions, with the period comparable to the wavelength of light. They have attracted substantial interest in the last decade due to their ability to inhibit spontaneous emission and control the flow of light. The best known example of a one-dimensional photonic crystal is the Bragg reflector, which can be constructed by deposition of pairs of layers, each a quarter of a wavelength in optical thickness, and each with a different refractive index. Recently, Bragg reflectors made with deep etching of air grooves through a planar waveguide have been employed to enhance the properties of a semiconductor laser [2].

Two-dimensional photonic crystals are usually made by etching air holes in a substrate; the resulting structure is similar to either a honeycomb or a periodic array of solid rods in air [3–7]. Various structures have been proposed that show a complete three-dimensional photonic band-gap (PBG), such as the diamond lattice of dielectric spheres [8], 'inverse opals' [9], 'yablonovite' [10], 'woodpiles' [11], and other more complex structures [12–14]. However, very few photonic structures displaying a PBG at the wavelengths of visible light have been realized, as construction on the scale of the wavelength of light of these often very complicated

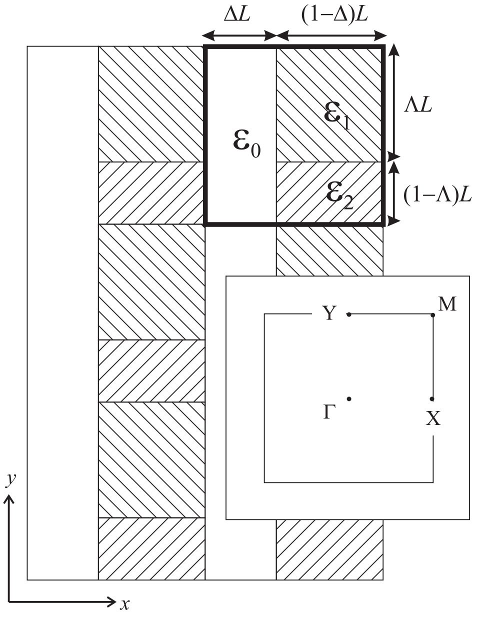

Figure 1. Schematic diagram of the structure of the etched Bragg reflector under consideration. The reflector can be constructed by taking the unit cell shown within the square box, and repeating it on a square lattice of points in the xy-plane. The inset is an illustration of the first Brillouin zone of the photonic crystal. The symmetry points are shown, and are located in k-space as follows—Γ: $\mathbf{k} = (0, 0)$; X: $\mathbf{k} = (\pi/L, 0)$; Y: $\mathbf{k} = (0, \pi/L)$; M: $\mathbf{k} = (\pi/L, \pi/L)$.

structures is technologically very challenging. Nevertheless, an inverse opal structure has been made that shows evidence of a complete PBG near 1.5 μm [15]. The inverse opal structure relies on self-assembly methods, and although it is possible to form a bulk photonic crystal like this, precise engineering of the crystal's properties is difficult. Thus, it is more desirable to be able to design photonic crystals based on epitaxial growth and etching methods, which are more controllable and well understood.

An attempt to design a technologically feasible 3D photonic crystal was made recently [16] by considering a structure of circular air rods etched along the growth direction of a distributed Bragg reflector. Although no complete PBG was reported, some structures did display a reduction in the density of photonic states by a factor of three when compared to a uniform medium with the same average dielectric constant. Etched Bragg reflectors thus provide a promising basis from which to try and design photonic crystals providing PBGs suitable for technological applications.

The aim of this paper is to study the mode structure of a 2D photonic crystal obtained by the deep etching of straight grooves parallel to the growth direction of the Bragg reflector, as shown in figure 1. Such a structure could be fabricated by the etching of deep air trenches (similar to those described in [2]) in a quarter-wave Bragg stack, which itself can be fabricated by molecular beam or gas-phase epitaxy. In such a structure there is combined optical confinement in both the vertical direction, and one of the lateral directions, and it could be used to improve the optical confinement in certain laser cavities. The unit cell of the structure is represented by a square with sides of length L, divided into three rectangular areas with dielectric constants ε_0, ε_1 and ε_2; the sizes of the three rectangles are described by two dimensionless parameters Δ and Λ, as shown in figure 1. Thus the structure consists of 'walls' made from materials with dielectric constant ε_1 and ε_2 separated by uniform grooves with dielectric constant ε_0.

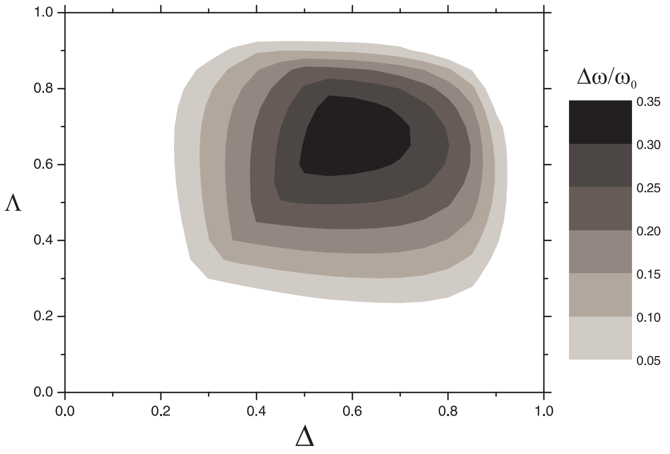

Figure 2. A 'gap-map' showing the calculated complete 2D photonic band-gap between the first and second E-polarized bands for etched Bragg reflectors with $\varepsilon_0 = 1.0$ (air), $\varepsilon_1 = 2.25$ (oxidized AlAs) and $\varepsilon_2 = 14.44$ (GaAs). The size of the photonic band-gap is shown as a ratio between the width of the gap and the centre gap frequency. The largest such band-gap is $\Delta\omega/\omega_0 = 0.338$ for the parameters $\Delta = 0.55$ and $\Lambda = 0.65$.

Electromagnetic waves propagating in 2D photonic crystals perpendicularly to the boundaries between the elements of the photonic crystal can be decoupled into two independent polarizations: E-polarized modes with field components (H_x, H_y, E_z) and H-polarized modes with field components (E_x, E_y, H_z).

Previously, PBGs have been reported for 2D photonic crystals—for E-polarized modes when the photonic crystal is made up of a square lattice of rods [3], and for H-polarized modes when the photonic crystal is made up of a connected lattice of dielectric veins [1] constructed by etching air holes of square cross-section in a square lattice. The structures studied in [1] and [3] possess four-fold rotational symmetry. In contrast, the etched Bragg reflector structure under study in this paper possesses no rotational symmetry, and the symmetry points X and Y (see figure 1) in the first Brillouin zone are not equivalent.

The dispersion relations (bandstructure) for the photonic crystal can be obtained by the plane wave method [4, 8, 17], while the transmission spectra can be calculated by a combination of transfer matrix and multiple scattering techniques [18].

To obtain a sizeable PBG, one should provide a sufficiently large contrast of the refractive index along both the Γ–X direction (perpendicular to the grooves) and Γ–Y direction (along the grooves). The air grooves have a dielectric constant equal to unity, and thus 'walls' made of any semiconductor material achieve the high refractive index contrast along the Γ–X direction automatically. Achieving the high refractive index contrast in the Γ–Y direction is a challenging, but feasible, task. A promising pair of materials are GaAs ($\varepsilon_2 = 14.44$) and oxidized AlAs (AlOx, $\varepsilon_1 = 2.25$).

In such a system, PBGs occur for E-polarized modes for certain values of the geometric parameters Δ and Λ defined in figure 1, but a PBG for H-polarized modes does not appear. Figure 2 shows the ratio of the width of the PBG ($\Delta\omega$) to the centre gap frequency (ω_0) for E-polarized modes as a function of Δ and Λ. The maximum width of the PBG relative to its centre frequency is equal to 34%, and occurs when $\Delta = 0.55$ and $\Lambda = 0.65$. Figure 3 shows dispersion relations, the density of E-polarized and H-polarized photonic modes and transmission spectra for such an optimized structure.

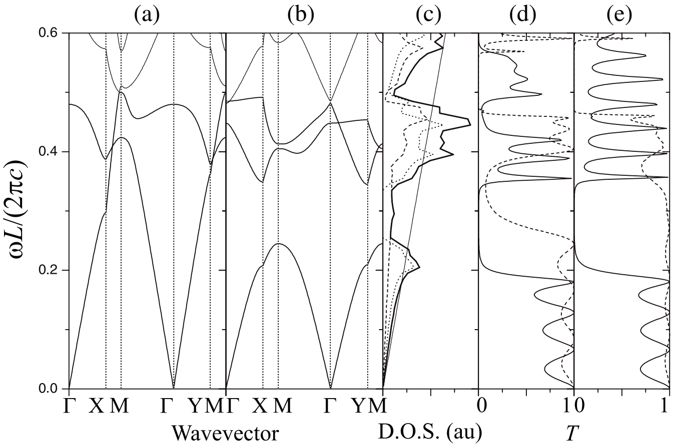

Figure 3. Calculated bandstructure for the H-polarization (a) and E-polarization (b), for the etched Bragg reflector with parameters $\varepsilon_0 = 1.0$ (air), $\varepsilon_1 = 2.25$ (oxidized AlAs) and $\varepsilon_2 = 14.44$ (GaAs), $\Delta = 0.55$ and $\Lambda = 0.65$. (c) The calculated density of states for the same structure. The dotted curve shows the density of E-polarized states, the dashed curve the density of H-polarized states, the heavy curve the total density of states and the straight line the density of states for a uniform medium with the same average dielectric constant as the etched Bragg reflector. (d) and (e) The calculated transmission spectra for light incident upon eight periods of the etched Bragg reflector in the Γ–X and Γ–Y directions, respectively. The two curves show the calculations for H-polarized light incident (dashed curve) and E-polarized light (solid curve).

It is seen that a large band-gap for all 2D directions occurs for the E-polarization, centred around $\omega L/(2\pi c) = 0.3$, but no such band-gap is observed for the H-polarization. The density of photonic modes reduces to zero for the E-polarization, and there is a pronounced stop-band in the transmission spectrum. In contrast, the transmission coefficient for H-polarized modes is close to one, no reduction of the density of H-polarized modes occurs, and the reduction of the total density of photonic states ρ (which is the sum of the densities of E-polarized and H-polarized photonic modes) compared to the density of states of an effective medium ρ_{eff} (characterized by the average dielectric constant of the structure) is not substantial. On the other hand, one can see a substantial reduction in the total density of photonic states near the frequency $\omega L/(2\pi c) = 0.5$. The rate of spontaneous emission of a quantum mechanical source inside the structure is given by Fermi's golden rule [19] and is proportional to the total density of photonic modes, and a substantial decrease of the spontaneous emission rate, rather than a total absence caused by a complete PBG, could be of value in certain device applications.

Varying the parameters Δ and Λ, we can change the position, width, and depth of this feature in the density of photonic states. Figure 4 shows the relative decrease of the density of states $\eta = \rho/\rho_{\mathrm{eff}}$ as a function Δ and Λ for the band of reduced density of states mentioned above. For $\Delta = 0.55$ and $\Lambda = 0.60$, the band of reduced density of states is centred near $\omega L/(2\pi c) = 0.5$. The relative reduction (η) becomes as small as 1/20, and the width of the band is 0.18 of its centre frequency. Although not a true PBG, such a substantial reduction in the density of photonic states provides a 'near-gap', and could be of use in some optoelectronic devices that rely on PBG materials.

Figure 5 shows the bandstructure, density of states and transmission spectra for an etched Bragg reflector with $\Delta = 0.5$ and $\Lambda = 0.5$. For this structure, the relative width of the region of the reduced density of states centred near $\omega L/(2\pi c) = 0.5$ reaches 0.23, while the relative reduction $\eta \approx 1/14$. Such a sizeable 'near gap' originates from a complete 2D band-gap for

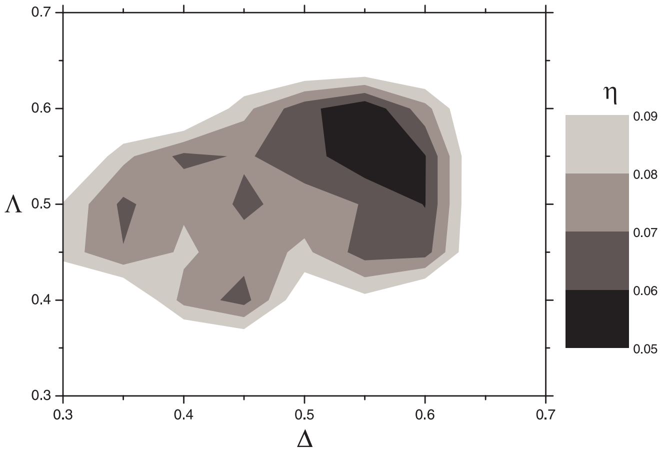

Figure 4. Graph showing the maximum relative reduction of the density of states of the feature near $\omega L/(2\pi c) = 0.5$ as a function of the parameters within the unit cell (i.e. $\eta(\Delta, \Lambda)$ in the text) for etched Bragg reflectors with $\varepsilon_0 = 1.0$ (air), $\varepsilon_1 = 2.25$ (oxidized AlAs) and $\varepsilon_2 = 14.44$ (GaAs).

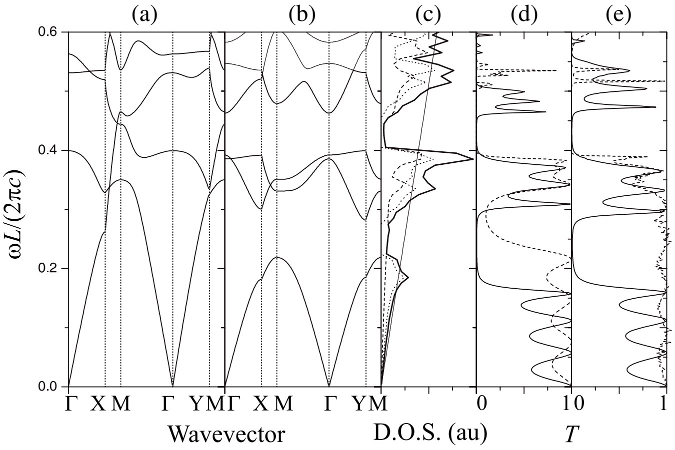

Figure 5. Calculated bandstructure for the H-polarization (a) and E-polarization (b), for the etched Bragg reflector with parameters $\varepsilon_0 = 1.0$ (air), $\varepsilon_1 = 2.25$ (oxidized AlAs) and $\varepsilon_2 = 14.44$ (GaAs), $\Delta = 0.50$ and $\Lambda = 0.50$. (c) The calculated density of states for the same structure. The dotted curve shows the density of E-polarized states, the dashed curve the density of H-polarized states, the heavy curve the total density of states and the straight line the density of states for a uniform medium with the same average dielectric constant as the etched Bragg reflector. (d) and (e) The calculated transmission spectra for light incident upon eight periods of the etched Bragg reflector in the Γ–X and Γ–Y directions, respectively. The two curves show the calculations for H-polarized light incident (dashed curve) and E-polarized light (solid curve).

the E-polarization and band-gaps along the Γ–Y and Γ–X directions for the H-polarization. In fact, in such a structure, only H-polarized light can propagate, and then only within a small angle near the Γ–M direction, if at a frequency corresponding to this near gap. The calculated transmission spectra for light propagating in the Γ–X and Γ–Y directions (shown in figures 5(d) and (e)) exhibit near zero transmission coefficients for the spectral region of reduced density of states.

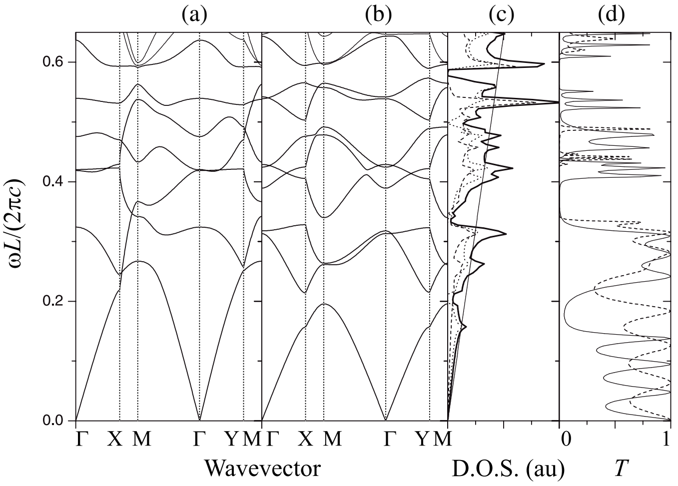

Figure 6. Calculated bandstructure for the H-polarization (a) and E-polarization (b), for the etched Bragg reflector with parameters $\varepsilon_0 = 1.0$ (air), $\varepsilon_1 = 2.25$ (oxidized AlAs) and $\varepsilon_2 = 14.44$ (GaAs), $\Delta = 0.30$ and $\Lambda = 0.35$. (c) The calculated density of states for the same structure. The dotted curve shows the density of E-polarized states, the dashed curve the density of H-polarized states, the heavy curve the total density of states and the straight line the density of states for a uniform medium with the same average dielectric constant as the etched Bragg reflector. (d) The calculated transmission spectra for light incident in the Γ–X direction upon eight periods of the etched Bragg reflector. The two curves show the calculations for H-polarized light incident (dashed curve) and E-polarized light (solid curve). A complete PBG in two dimensions can be seen centred around $\omega L/(2\pi c) = 0.58$.

Although the etched Bragg reflectors possess no rotational symmetry, the structures considered in figure 4 (with parameters $\Delta \approx 0.5$ and $\Lambda \approx 0.5$) do possess an approximate rotational symmetry. This approximate rotational symmetry arises due to two of the materials which constitute the Bragg reflector having similar dielectric constants, i.e. $\varepsilon_1 \approx \varepsilon_2$. The approximate rotational symmetry manifests itself in a near isotropic dispersion, especially for the low frequency E-polarized bands (see figures 3(b) and 5(b)). It also results in very similar transmission spectra for the E-polarized modes in both the Γ–X and Γ–Y directions. For example, the E-polarized modes for the structure with $\Delta = 0.5$ and $\Lambda = 0.5$ (solid curves in figures 5(d) and (e)) both have near zero transmission for the spectral regions centred on $\omega L/(2\pi c) \approx 0.23$ and $\omega L/(2\pi c) \approx 0.42$. The corresponding transmission spectra for H-polarized light differ for low frequencies, as there is no band-gap in the Γ–Y direction, and thus no stop-band appears in the spectrum.

Whilst no complete photonic band-gaps have been found for both polarizations between low lying photonic bands, certain values of the parameters Δ and Λ do give complete band-gaps between higher frequency photonic bands, but these gaps are very narrow (typically about 2–3% of the mid-gap frequency) and only occur for highly restrictive values of Δ and Λ. For example, the structure with $\Delta = 0.30$ and $\Lambda = 0.35$ has a complete band-gap for H-polarized modes between the sixth and seventh photonic bands, and a complete band-gap for E-polarized modes between the eighth and ninth photonic bands (see figure 6 for the bandstructure, density of states and calculated transmission spectra). These band-gaps overlap each other to give a complete 2D PBG for both polarizations with a width of 2.8% of the gap centre frequency. Although these band-gaps are narrow, the result demonstrates that an etched Bragg reflector structure is capable of supporting complete PBGs, and that if materials with a greater refractive index contrast were used, these band-gaps could open up to a more technologically useful size.

It is worthwhile considering a structure in which the etched grooves in the Bragg reflector are filled by some material other than air. For example, filling the regions with AlAs ($\varepsilon_0 = 9.0$) gives a structure that resembles a 'connected' lattice of high-ε material in a low-ε background, and in which it should be possible to find band-gaps for H-polarized modes [1]. This structure is complementary to the structure considered previously, which had high-ε rods in a low-ε background. However, the values $\varepsilon_0 = 9.0$, $\varepsilon_1 = 2.25$ and $\varepsilon_2 = 14.44$ fail to provide sufficient contrast between the high-ε and low-ε regions, and no H-polarized band-gaps are found. To increase the contrast, consider the structure in which the oxidized AlAs is removed to leave air in its place ($\varepsilon_0 = 9.0$, $\varepsilon_1 = 1.0$ and $\varepsilon_2 = 14.44$). This structure gives a band-gap for H-polarized modes, and the maximum value of the relative width of the gap, equal to 0.26, is achieved when $\Delta = 0.2$ and $\Lambda = 0.8$.

In conclusion, we have considered etched GaAs/oxidized AlAs (AlOx) Bragg reflectors as 2D photonic crystals, and found that in such structures a complete photonic band gap for E-polarized modes can occur. Also, we have found that structures can be engineered to provide a reduction of the total density of states by a factor of 20 compared to a uniform medium with a dielectric constant equal to the average value of the structure. It is also found that very narrow complete photonic band-gaps can be seen for both polarizations, for certain restricted values of the parameters of the structure.

Acknowledgments

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