Photonic Crystal Defect Cavity Q-Factor Optimization Using Slab Thickness

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Abstract— **Three mechanisms are studied which give rise to a high-Q L3 cavity mode in a 2D photonic crystal slab where the in-plane photonic bandgap is closed due to increased slab thickness.**

Keywords-component; Photonic Crystals; Quality-factor; 2D Photonic Crystal Slab Cavities

I. INTRODUCTION

There has been much interest in the design of high Quality (*Q*) factor, low mode volume (*V*) photonic crystal (PhC) defect cavities in many different wavelength ranges and material systems. In our work, optical resonators are constructed by removing three holes from a 2D PhC composed of a hexagonal lattice of air holes in a slab of AlGaInSb, which is a promising candidate for the realization of room temperature lasers emitting in the 3-4μm region [1]. Such structures are typically designed so that the slab thickness is chosen so that only the lowest-order optical mode in the vertical direction is supported [2]. However, in the case of *Q* factor, a number of studies have shown that thicker slabs can lead to stronger confinement [3,5]. Here, the 3D Finite-Difference Time-Domain (FDTD) and frequency-domain Plane Wave Expansion (PWE) methods have been used to study of the effect of slab thicknesses which exceed that for single vertical mode propagation. A new structure design is suggested which allows high-*Q* PhC cavity modes to exist where there is no bandgap by choosing slab thicknesses equal to a multiple of half the guided mode wavelength [3]. In this case we believe the three confinement mechanisms of (i) "Gentle" in-plane confinement, (ii) Minimisation of overlap to in-plane Bloch modes and (iii) Vertical cavity resonance coincide to give rise to very high *Q*-factors.

II. PHOTONIC BANDGAP & L3 CAVITY DESIGN

Light can be localized in all three dimensions using the combination of a 2D photonic crystal and a slab with a lower refractive index medium, such as air, above and below [4]. To create a photonic bandgap as a function of the in-plane Bloch wave vectors, as seen in figure 1(a), a uniform 2D pattern of holes in a slab of thickness, *d*=1μm and refractive index, *n*=3.826, is designed using RSoft BandSOLVE (BS) PWE simulations to forbid the transmission of light at the desired wavelength. The structure is not periodic in the y-direction but it does have a symmetry plane through the centre of the slab, therefore we can apply parity to the simulations and view only those Bloch modes that are even with respect to the y-parity – i.e. the E-field is perpendicular to the hole axis. Band diagrams at this thickness show there is no photonic bandgap due to the 2nd-guided band dropping below the lowest-order band edge in terms of frequency. The figure also shows the position for the two resonant modes in an unmodified L3 cavity. Figure 1(b) shows results from 3D band solving with superimposed 3D FDTD results (uniform mesh cell size 50nm), showing the position of resonant modes relative to the upper and lower band edges. These results show that at a thickness of 1μm a PBG no longer exists.

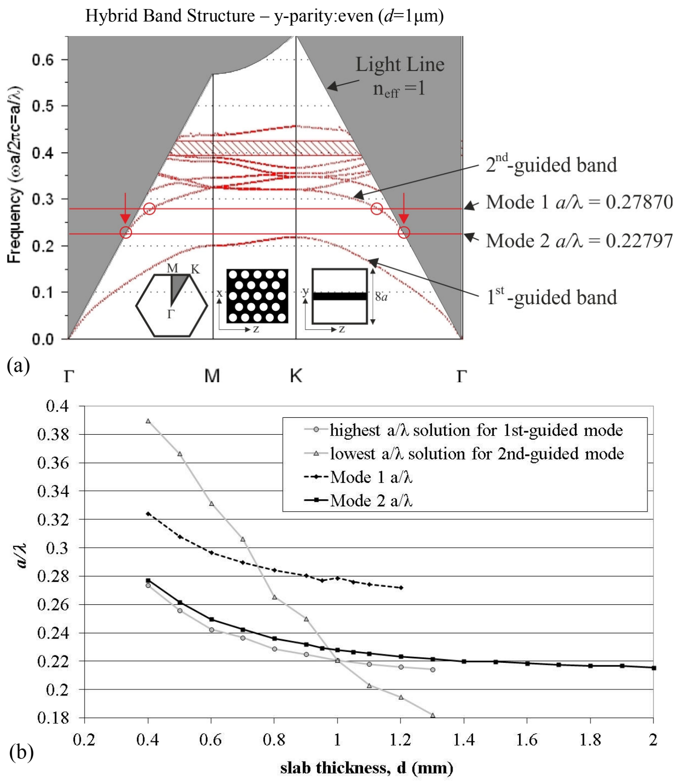

Figure 1. (a) 3D Dispersion diagram for modes with even y-parity of a 2D PhC slab composed of a hexagonal lattice of air holes, slab thickness, *d*=1μm, *r/a*=0.35, *a*=0.884μm, *n*=3.826. Insets show *k*-space lattice along with irreducible Brillouin Zone (shaded grey) and real-space representations of the slab in the y- and x-planes. (b) 3D PhC band diagram solutions for the even y-parity bandgap at varying *d*.

Whilst the effect of slab thickness exceeding that for single vertical mode propagation has been studied for single defect cases, our work [5] is the only example for L3 defects that can result in very high-Q factors due to gentle confinement of the mode [6]. The cavity geometry is elongated in the z-direction as shown in figure 2(a) and in Pugh *et al* [5], where three thicknesses of slab were investigated in detail: 400nm, 800nm and 1µm. The interesting result is seen for d=1µm and the effect of displacing the outer holes of the L3 cavity at this thickness.

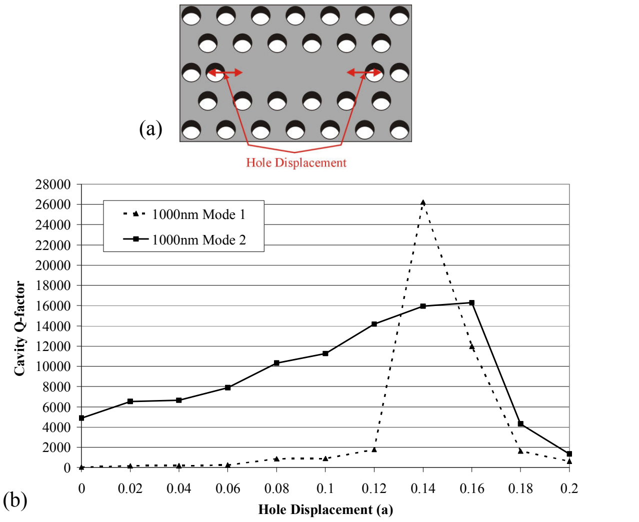

Figure 2. (a) Outer-hole displacement of an L3 defect cavity in a 2D hexagonal PhC [5]. (b) The effect of displacing the outer holes of the L3 cavity along z for the 1µm thick slab.

is shown in figure 2(b) – two modes are strongly confined at 0.14a displacement, mode 1 at λ=3.375µm with a Q~2.7x10^3 and mode 2 at λ=3.914µm with a Q~1.6x10^3. The position of these two modes in relation to the 3D bandgap is shown in figure 1(b). Displacing the holes plays two roles – Firstly, the E-field profile across the cavity in real space becomes more closely Gaussian in shape for the high Q cases, minimizing the E-field within the light-cone in k-space [6]. Secondly, the resonance wavelength shifts aligning it with the vertical cavity resonance for a particular slab thickness – an effect which gives the otherwise low-Q mode 1 a dramatic increase in Q at particular hole displacements. Figures 3(a) and (c) show real space representations of the $|E_x|$-field amplitude of mode 1 through the centre of the cavity in the y- and x-planes respectively. A further representation of mode 1, which is important for explaining the origin of the high-Q is the abs(E_x(re))-field through the centre of the cavity plotted in k-space shown in figure 3(b). First suggested by Srinivasan *et al* [7], this representation of the mode can quantify its losses through propagation into the light cone (solid line). Importantly in this paper, it also allows the losses into the 2nd-guided band of the PhC to be quantified by overlapping its k-path length onto figure 3(b) (dashed line) – the abs(E_x(re))-field here is very small. Therefore, increasing the slab thickness beyond the maximum thickness for only lowest-order optical mode in the vertical direction to propagate (d~460nm) and beyond the thickness for a full 3D even mode bandgap nevertheless allows for a high-Q PhC cavity mode to propagate.

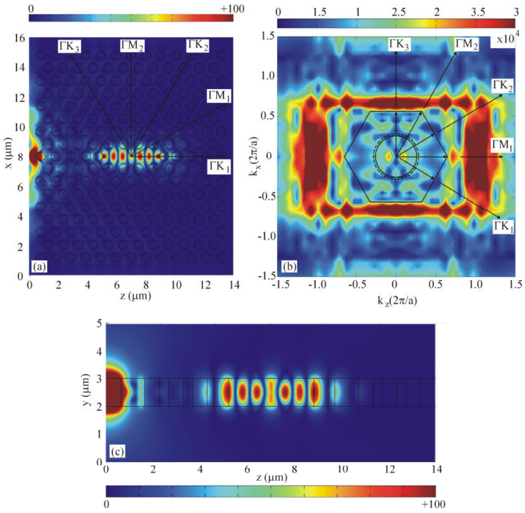

Figure 3. FDTD frequency snapshot representation of the behaviour of mode 1 at 0.14a hole displacement through the centre of the cavity in the (a) y- and (c) x-planes. (b) shows the abs(E_x(re)) k-space plot of (a).

III. CONCLUSIONS

This paper presents a study of two resonances in a modified L3 PhC slab cavity in a slab of thickness 1µm – mode 1 at λ=3.375µm with a Q~2.7x10^3 and mode 2 at λ=3.914µm with a Q~1.6x10^3. It is the behaviour of mode 1 that makes this study especially unique – a sudden rise in cavity-Q (beyond that of mode 2) is observed where no bandgap exists for the mode; this was found when changing the cavity geometry to a point where three confinement effects are believed to coincide: (i) There were small $|E_x|$-field components within the light-cone – a consequence of a nearest-Gaussian $|E_x|$-field distribution along the cavity of hole displacement cases, (ii) Small amounts of overlap between the cavity mode and the 2nd-guided band when viewed in k-space and (iii) Good vertical cavity resonance, where the guided wavelength approximately equalled the slab thickness. This high-Q is extremely sensitive to any change in cavity or slab properties which could be a useful property in switching or sensing applications. It is also an important result in terms of the fabrication of slab devices, since thin slabs can be very fragile and having high-Q cavity modes available in thicker slabs will make them more robust.

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