Investigation of photonic crystal cavities sandwiched in a grating structure

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Abstract - *By sandwiching a high Q photonic crystal cavity in a grating structure, the Q can be increased with about 150% compared to a silica background, since certain Fourier-components inside the leaky light cone are now resonating in the vertical resonant structure.*

Introduction

Design of high Q cavities, together with a small modal volume, is crucial for photonic integration. High Q values of the order 10^5 - 10^6 have already been designed in the air-bridge structure. The methodology used is nearly always the same. As proved in [1], the Q values can be very high, by shifting holes or reducing the hole size so that the reflection coefficient is not steep, but gradual. The abrupt change introduces a lot of leaky components while when having a gradual reflection these components are shifted out of the light cone and are no longer leaky.
In the present paper, this methodology is used again and furthermore a vertical cavity is designed to increase the Q value. In a first stage an attempt is made to increase the Q factor by putting a SiO_2-SiN grating around the cavity. This grating results in forbidden regions for which light can not propagate. The effect of changing the gap-center frequency of the grating is investigated. In a later stage, the first SiO_2 layer is increased in thickness resulting in a resonant cavity. Afterward the effect of a SiO_2-Si grating is investigated.
The Q cavities are simulated with the FDTD software and the Q-values are calculated with a Padé approximation [2]. The refractive index of Si, SiO_2 and SiN are 3.6, 1.45 and 2 respectively. The air holes in the photonic crystal slab have a radius of 0.3a and the slab thickness is 0.6a. All the distances given in the present paper are normalized to *a*, the lattice constant of the photonic crystal.

Investigation of the vertical structure

The vertical structure is investigated by first changing the grating surrounding the photonic crystal slab. The grating will be specified by its gap-center frequency. Afterward the first SiO_2 layer of the grating is tuned. This is visualized in Fig. 1. The vertical structure is analyzed by means of the Transfer Matrix Method in which the starting point is the center of the photonic crystal slab. For the SiO_2-SiN grating 10 grating periods are taken, for the SiO_2-Si grating 5 grating periods are sufficient for the saturation of the Q value.

M1 cavity

The structure under investigation is the M1 cavity, one missing hole with H_z even in the x, y and z-direction. This cavity supports one high Q mode in the air-bridge structure

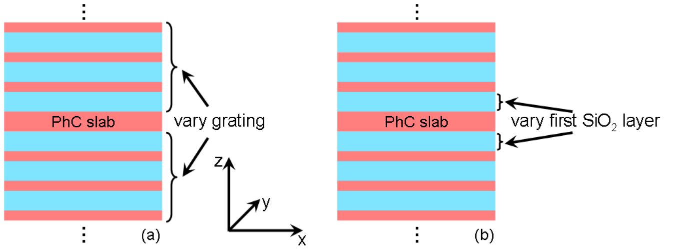

Figure 1: Design procedure of the vertical structure: (a) the gap-center frequency of the grating is tuned, (b) the thickness of the first SiO_2 layer is tuned.

of 37000 for shifted holes of 0.20a with a frequency of 0.292c/a. The field profile is shown in Fig. 2(a). When having a silica background on both sides, in order to keep the symmetry, the Q reduces to 2800 at a hole shift of 0.23a at a frequency of 0.286c/a.

The structure is now surrounded by a grating for a hole shift of 0.22a and 0.25a with a

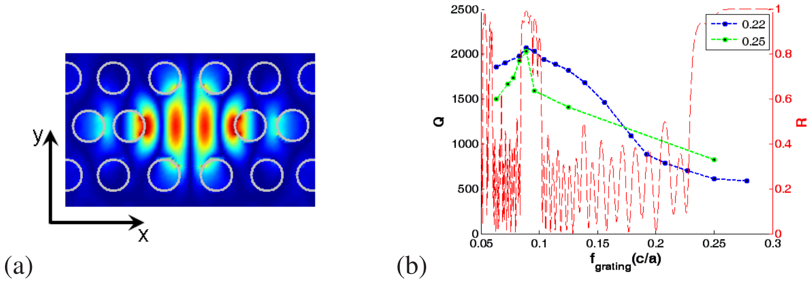

Figure 2: (a) Field profile of $|E_y|$ for the M1 cavity in air for a hole shift of 0.20a. (b) Q values of the M1 cavity for a hole shift of 0.22a and 0.25a when shifting the gap-center frequency of the surrounding grating. The reflection coefficient at the center of the PhC slab for a frequency of 0.292c/a and an in plane k_{xy} of 0.4π/a is shown in the red graph.

corresponding mode frequency of about 0.296c/a and 0.292c/a respectively. The resulting Q factors are shown in Fig. 2(b). When the gap-center frequency of the grating equals the frequency of the mode, the Q is rather low ($\sim$ 500). This is due to the fact that the SiN slab is rather close to the photonic crystal slab and so part of the light that decays exponentially into the silica will be guided again in the SiN resulting in increased losses. When lowering the gap-center frequency of the grating, the grating layers increase in thickness and the first SiN layer is further away from the silicon slab resulting in an increase in the Q value. The Q value stays however below that of the structure with a silica background. A maximum can be seen around a grating gap-center frequency of 0.089c/a. This can be explained due to the fact that the gap-center frequency of the grating is then about one third of the mode frequency, so the grating is again highly reflective. If the effect that the mode does not radiate at perpendicular incidence but at small angles is taken into account, it can be seen in Fig. 2(b) that for an in plane Fourier component k_{xy} of 0.4π/a, the high reflectivity of the grating corresponds with the maximum in Q value. The Fourier transform of the M1 mode surrounded by a grating with a gap-center frequency of 0.089c/a is shown in Fig. 3(a). Since the mode will only feel the surrounding silica, the silica light cone is depicted instead of the effective index light cone of the grating. The above result suggests that it is important for the grating to reflect at approximately the mode frequency while keeping the first higher index slab far enough from the PhC slab. When having a lower gap-center frequency of the grating, other k-components are forbidden to propagate into the grating, but this does not imply that this light will reflect back into the mode volume. The band diagrams of the gratings are shown in Fig. 4. For the grating with $f_{gap-center} = 0.089$c/a the forbidden region near $k_{xy} = 0.4\pi$/a is visible for which we saw (Fig. 2(b)) the structure was highly reflective. The first forbidden region in 4(a) however extends much further and it is only due to the fact that the SiN is so close to the PhC slab that losses occur.

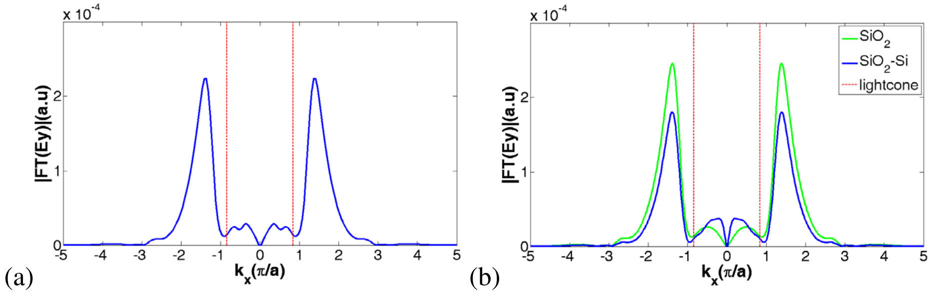

Figure 3: 2D Fourier transforms of the M1 mode in a grating structure along the k_x axis. The red dashed line denotes the silica light cone: (a) grating structure with gap-center frequency of 0.089c/a, no tuning of the first SiO_2 layer (hole shift 0.24a). (b) SiO_2 background (hole shift 0.23a) and 0.6207a SiO_2 - 0.250a Si grating (hole shift 0.25a) with first SiO_2 layer thickness of 2.3a.

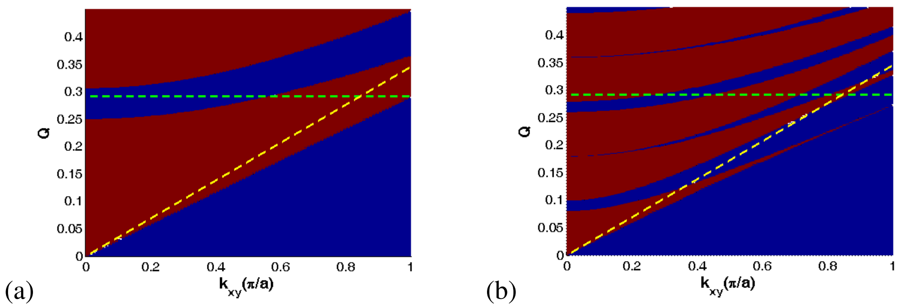

Figure 4: Band diagram of the gratings. Blue areas are forbidden regions. The green dashed line denotes the mode frequency, the yellow dashed line denotes the silica light cone. (a) grating 0.6207a SiO_2, 0.450a SiN: $f_{gap-center}$=0.278c/a, (b) grating 1.9130a SiO_2, 1.400a SiN: $f_{gap-center}$=0.089c/a.

The only possibility to effectively increase the Q is by having an extra resonance in the vertical structure. Therefore not only high reflection is needed, but the phase condition should be met as well. For this the first SiO_2 layer is shifted as denoted in Fig. 1(b). For the following, focus is pointed to a hole shift of 0.25a. The results are shown in Fig. 5. It can be seen that the highest Q values appear when the reflected light is in phase with the original field. The phase shown is for perpendicular incidence since the only way to improve the Q is to have an extra resonance in the vertical direction and as can be seen in Fig. 3(b), the main k-components inside the light cone are near $k_x = 0$. The maximum Q values obtained are 3000 and 4000 for the SiO_2-SiN and SiO_2-Si grating respectively. The SiO_2-Si grating gives a higher Q than the SiO_2-SiN grating since the former is more broadband and will be highly reflective for more k-components inside the light cone. The first maximum is lower than the second since for this maximum the higher index SiN/Si slab is too close to the PhC slab. In Fig. 3(b) the 2D Fourier transform of the M1 mode

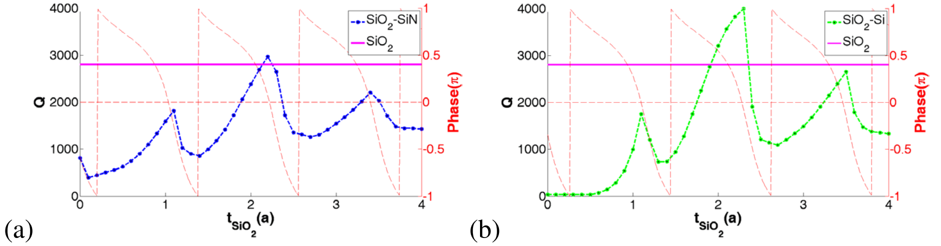

Figure 5: Optimization by shifting the thickness of the first silica layer. The red graph shows the corresponding phase of the light reflected back from the center of the photonic crystal slab for perpendicular incidence, $k_{xy} = 0$; the solid magenta line shows the Q value in the case of a silica background: (a) 0.6207a SiO_2 - 0.450a SiN grating, (b) 0.6207a SiO_2 - 0.250a Si grating.

along the k_x-axis is shown when the PhC slab is surrounded by silica and when it is surrounded by the SiO_2-Si grating with tuned first SiO_2 so that the Q is maximal. This graph clearly shows that the k-components are not decreased within the light cone, but they are on the contrary bigger. The light near $k_x = 0$ is however resonating in the vertical direction and therefore stays confined.

Conclusion

The effect of putting a PhC slab inside a grating structure is investigated for microcavities. By using a SiO_2-Si grating and ensuring phase match in the vertical direction, the Q value could be increased compared to a silica surrounding. This is mainly due to the fact that, instead of reducing light leakage, part of the leaky light resonates in the vertical cavity.

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