Design of high-Q Cavities in Photosensitive Material-based Photonic Crystal Slab Heterostructures

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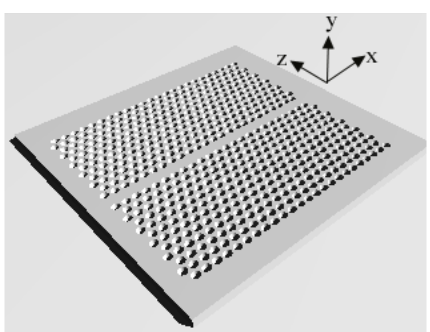
Abstract— We propose a novel concept for creating high-Q cavities in photonic crystal slabs (PCS). We show that photonic crystal slab-based double heterostructure cavities, formed by variations in the refractive index, can have large a Q-factor (up to $Q = 1 \times 10^6$), and that such cavities can be implemented in chalcogenide glasses using their photosensitive properties.

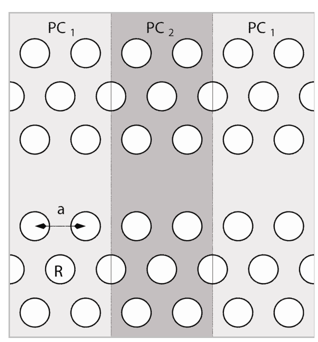
DOI: 10.2529/PIERS060907042030

In the last few years the study of optical microcavities based on photonic crystal slabs has attracted much attention [1–10]. Almost all of these studies consider a PCS composed of a hexagonal array of cylindrical air holes in a high-index semiconductor slab. There are many possible device applications of compact and efficient PCS nanocavities, such as channel drop filters [1], low-treshold laser [5], and cavity QED experiments [6, 7]. The principal design aim for all these applications is to obtain a high quality factor within a small modal volume.

A cavity is usually formed in either of two ways: forming a point cavity or forming a "heterostructure". Microcavities with the highest Q values achieved to date, have been realised through the use of photonic crystal double-heterostructures [9, 10], where regions of slightly different lattice constant are combined in a single slab to create a cavity. Song et al., constructed double heterostructure PCS, in which a short length of crystal (PC_2) with a lattice constant stretched in one direction, interrupts the main crystal (PC_1) [9, 10] (see Fig. 1).



(a)

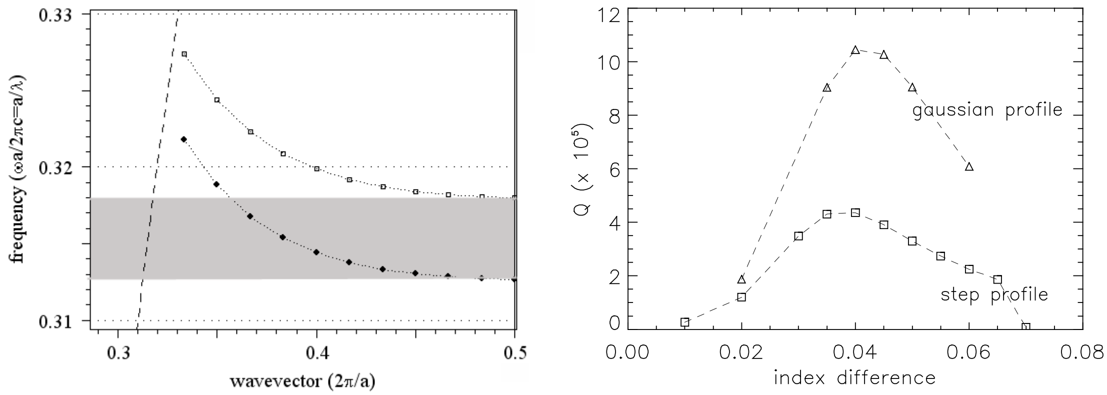


(b)

Figure 1: (a) Schematic of PCS with a W1 waveguide in the Γ-K direction and (b) refractive index distribution in the plane of the structure considered. The central darker region indicates the increased index.

It is possible to form heterostructures exploiting material properties, rather than the geometry of the structure. In this paper we consider a chalcogenide glass-based PCS. It has been already shown that high quality PCS can be fabricated in this material [11]. The key property here is that chalcogenide glasses are photosensitive. This means that the refractive index of the material can change by 1 to 8%, depending on the type of glass, when it is illuminated by light, typically in the visible part of the spectrum [12].

The concept of the cavity design in hetero-structures relies on the mode-gap effect, a narrow frequency range for which PC_2 supports a mode, but not PC_1. Therefore, first we determine if there is a sufficient mode-gap to support a localized state between the structures having different refractive indices. We introduce a W1 waveguide in these structures: $W1_1$ for PC_1 with $n = 2.7$, and $W1_2$ for PC_2 with $n = 2.75$. Using the Plane Wave Expansion method, we obtain the dispersion curves. The results are shown in Fig. 2(a). The size of the mode-gap is comparable to those of the hetero-structures formed by geometric variation [10]. This suggests that hetero-structures formed by photosensitive index enhancement should also be capable of supporting localized states.



(a) (b)

Figure 2: (a) Dispersion curves for W1 of PC_1 (empty square) and W1 of PC_2,(full circle) within the region of the lowest gap; the dashed line represents the light line and (b) quality factor Q as a function of the refractive index difference between PC_2 and PC_1 for a step profile(square) and for a Gaussian profile (triangles).

Now we calculate quality factors for the structure illustrated in Fig. 1, for different cases where the refractive index change of the central part varies from $\Delta n = 0.01$ to $\Delta n = 0.07$. The results are shown in Fig. 2(b), where we see that a refractive index change as small as $\Delta n = 0.01$ is enough to obtain a quality factor $Q = 3 \times 10^4$, whilst increasing the refractive index difference to $\Delta n = 0.02$ increases the quality by a factor four. The maximum quality factor that we calculated— $Q = 4.3 \times 10^5$—appears at $\Delta n = 0.04$. The associated resonant frequency $\tilde{\varnothing} = 0.3157$ is located in the middle of the mode gap in Fig. 2(a). A further increase in the refractive index decreases the quality factor, but the Q factors are still of the order of 105. It is interesting to note that quality factors of $Q \sim 10^5$ are achieved with large refractive index changes of $0.02 < \Delta n < 0.065$. As expected, the quality factor in chalcogenide glass-based PCS is smaller than for the silicon-based PCS, due to the smaller refractive index [7].

We also modelled a cavity with a Gaussian index variation (full-width at half maximum $2a$) along the waveguide direction, with identical maximum refractive index differences to those for the step profile. The results are plotted in Fig. 3. The maximum quality factor, $Q = 1 \times 10^6$, appears when the maximum refractive index change $\Delta n = 0.04$, just as for the step profile. Therefore changing the refractive index profile from a step to a Gaussian profile more than doubles the quality factor. This is consistent with findings of Song et al., who reported that a gradual structural change produces higher quality factors [9].

In conclusion we suggest a novel way of obtaining hetero-structures that can be applied to the PCSs made from photosensitive materials, such as chalcogenide glass and polymer. The hetero-structure is composed of elements that slightly differ in the refractive index; in practice this index difference can be easily photoinduced. We demonstrate that the chalcogenide-based PCS hetero-structure, designed in this way, can exhibit extremely high cavity mode localization due to the mode-gap effect. We also demonstrate that the nanocavities in these structures can reach ultrahigh-Q quality factors.

ACKNOWLEDGMENT

This work was produced with the assistance of the Australian Research Council (ARC) under the ARC Centers of Excellence Program. CUDOS (the Centre for Ultrahigh-bandwidth Devices for Optical Systems) is an ARC Centre of Excellence.

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