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Photonic Crystal Cavities for Sensing: Dielectric Modes versus Air Modes

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Abstract: Effective sensing with photonic crystal cavities requires optimization of modal quality factor and field overlap. For several unrelated cavities, we find the quality factor dominates, so that dielectric modes are strongly favored over air modes.

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1. Introduction

Optical cavities have been developed in a wide range of geometries [1] but the platform that enables the most compact cavities is the photonic crystal slab (PCS). The high quality factor, small modal volume and precise design control available in PCS cavities promises applications in areas as diverse as optical telecommunications and cavity quantum electrodynamics. Our interest here is the area of bio-chemical sensing [2].

Optical cavity-based sensors rely on the wavelength shift of the cavity resonance associated with the refractive index change induced by the sample. In bio-chemical applications, this change is invariably small. The *sensitivity* S, given by the ratio of the wavelength shift to the refractive index change, is proportional to the energy fraction of the resonant mode field f that interacts with the sample [2], and thus it is natural to maximize the fraction f. However, for effective operation, cavity-based sensors must provide a shift larger than the resonant mode linewidth. Since the linewidth is determined by the quality factor Q, it also plays a critical role and it is actually the figure of merit $F=fQ$ which must be optimized [2]. In PCS structures, Bloch states at the lower band gap edge form *dielectric bands*, concentrated in the high index material. Resonant cavity modes *close* to the lower band gap edge share this character, and have a small overlap between the field and the sample, but typically have high-Q. In contrast, resonant modes close to the upper band gap edge have a large overlap between the field and the sample but are usually low-Q modes [2]. Therefore, the figure of merit involves competing effects and an optimization is required. Moreover, the favored mode may depend on the class of cavity being considered. In this paper we compare the performance of the dielectric and air mode for two types of cavity: a point [3] and a double-heterostructure type cavity [4,5], and determine which effect dominates.

2. Results

We consider a two-dimensional silicon photonic crystal slab (PCS) composed of a hexagonal array (period a) of cylindrical air holes with radius R and two types of cavity: a confined band edge point cavity [3] and a double-heterostructure type cavity [4]. For each cavity, we investigate the performance of dielectric and air bands.

Confined band edge point cavity: The structure consists of air holes ($R=0.4a$) patterned in a slab of thickness $h=0.42a$ and relies on the trapping of a dielectric or air bandedge mode. In a perfect PCS these modes are delocalized. However, they may be confined spatially by modifying the hole radius in the central *core* region of the crystal as described in [3]. To confine a dielectric (air) mode the air hole radius in the core region R_c needs to be larger (smaller) than in the rest of the PCS. In the present work we have $R_c=0.5a$ for the dielectric mode and $R=0.36a$ for the air mode. Following the design of [3], adaptation rings may be added around the core to smoothen the variation in hole radius from the core to the bulk of the PCS and so increase the Q factor, with minimal change in the modal volume.

Double-heterostructure (DH): The structure has holes radius $R=0.31a$ (air-mode) or $R=0.29a$ (dielectric mode), with slab thickness $h=0.6a$. A line defect in the form of W1 waveguide in the Γ-K direction cuts across the PCS. Starting from a homogeneous PCS, the DH is formed by air-hole infiltration (indicated by the dark circles in Fig. 1(b)). The infiltrated region length is $L=6a+2R$, similar to previously demonstrated infiltration cavities [5].

We evaluate the cavity properties using the 3D FDTD method. For the point cavity, all holes are infiltrated with water, $n_f=1.33$, whereas for the DH, the cavity region is *defined* by the infiltrated zone of length L see Fig. 1(b). On

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adding the sample, the refractive index of the liquid changes slightly, shifting the cavity's resonant frequency. We define the sensitivity of the mode as the ratio of the frequency shift $\Delta\omega$ and the spectral linewidth $\delta\omega$, so that:

$$S = \frac{\Delta\omega}{\delta\omega}, \qquad \delta\omega = \frac{\omega}{Q}\cdot \tag{1}$$

We assume that the detectable response has sensitivity larger than 0.5 (which is a conservative estimate of a detectable shift of the spectral features of the cavity according to the generally accepted criterion for the minimum resolvable detail). The fraction of the resonant mode field that interacts with the sample is calculated using the first order approximation [2]:

$$f = \frac{n_f}{\lambda}\frac{\delta\lambda}{\delta n} \tag{2}$$

In Fig. 1, we show the sensitivity versus the refractive index range caused by the presence of the sample. Note that for both cavities the sensitivity is larger for the dielectric mode than for the air mode. This is because the *Q* of the dielectric mode is much larger than that of the air-mode. For the band edge cavity mode, for example, for the dielectric mode Q=1.3×10^6 and f=14%, while for the air mode Q=8.8×10^4 and *f*=44%. Thus the larger overlap with the sample of the air mode, is more than offset by the ratio of the *Q*'s.

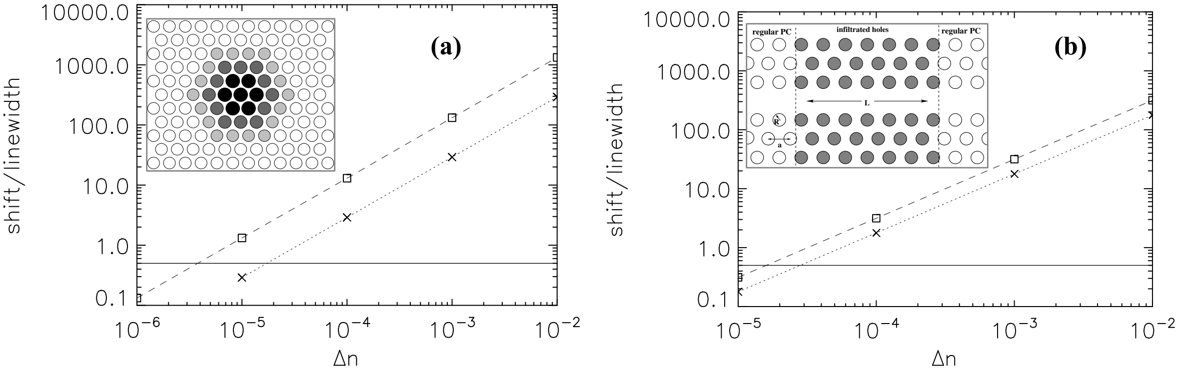

Fig. 1 Sensitivity of the air-mode (crosses) and dielectric mode (squares) for (a) the band edge cavity and (b) double-heterostructure type cavity as a function of the refractive index change. The insets show the schematic of the cavities.

The results presented here are not optimized. It is possible to increase both the *Q* and *f* further, for example by narrowing the waveguide width in the DH type. There are other possible PCS configurations that can provide relatively high-*Q*s and at the same time large *f* such as a DH with a slot in the middle of the waveguide [7], but the slot is quite narrow so it may be hard to infiltrate. In general however, we observe that the quality factor responds exponentially to small design changes, while typically $f > 0.2$ and cannot exceed unity. Almost invariably, then, we can expect that optimizing *Q* at the expense of *f* is likely to be beneficial, and dielectric bands are thus preferred.

3. Conclusions

We have compared the dielectric and air-mode sensitivity for two different types of the PCS cavities. Although a good overlap between the field and the fluid is necessary our results show that it is not the most crucial factor. Ultimately the sensitivity of a PC cavity relies on *both* the overlap between the field and the region containing the analytes and the quality factor. Because high-*Q* PCS cavities are easier to design with dielectric modes than with air modes, and because there already exists a wealth of experience in the fabrication of PC cavities supporting dielectric modes for active devices, our study suggests that dielectric modes, not air modes, are the most "cost-effective" platform to design PCS sensors.

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