Hybrid photonic crystal cavity modeling exercise

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Introduction

The objectives of this exercise are to study a promising hybrid cavity design, and to compare different simulation tools in the handling of the 3D cavity problem. The design is an extension of the novel and interesting ladder cavity structure [1], which combines a fairly simple understanding and geometry, with very good cavity properties (quality factor, mode volume. . .). This type of linear cavity is formed by a chirped, symmetric ladder profile, which gently confines a mode in the center by photonic bandgap shifts.

Here, we study a hybrid extension of the cavity (Fig. 1), meaning that we try to combine different material systems. More specifically, we add a parallel, straight waveguide underneath the resonator, which can function as an input and output channel. The hybrid character stems from the use of different materials for cavity and waveguide. In our exercise we assume a silicon waveguide (Si, $n = 3.46$), resting on a (semi-infinite) silicon oxide layer (SiOx, $n = 1.45$). The cavity is formed by sections of indium phosphide (InP, $n = 3.17$). On top of the oxide substrate and all around the cavity we have a homogeneous material, in our case we take the bonding material BCB (benzocyclobutene, $n = 1.54$). Remark that with this system the structure is experimentally realizable.

The central parameter here is the quality factor Q of the cavity, and we mainly investigate its evolution when the Si waveguide is adjusted.

Geometry

The following parameters remain fixed throughout (Fig. 1): $\text{InP}_y = 0.7\mu\text{m}$, $\text{InP}_z = 0.35\mu\text{m}$, period $= 0.35\mu\text{m}$, $\text{Si}_z = 0.22\mu\text{m}$. Some of the ladder properties are also fixed. We keep the center positions of the veins constant (always one period apart), but we vary their longitudinal thickness (along x). The unmodulated 'mirror' veins on each side have width (in the x-direction) $w_{mir} = 0.2\mu\text{m}$. We use 10 mirror veins ($N_{mir} = 10$) on each side (although this exact number should not influence the results too much). An important parameter is N_{cav}: the number of modulated veins *on each side* of the center, so in total there are $2N_{cav}$ veins in the cavity with slightly smaller widths. The center of the cavity is in BCB, in between the first two veins, which have the same width. The modulated cavity vein widths are

$$w(i) = w_{cav}\left[1 + \frac{(i-1)^2}{3N_{cav}^2}\right], \tag{1}$$

with $w_{cav} = 0.15\mu\text{m}$ and $i = 1 \dots N_{cav}$. So e.g. for $N_{cav} = 3$ the vein width sequence (in μm, rounded to 3 digits) is :

$$[(10\times)0.2, 0.172, 0.156, 0.15, 0.15, 0.156, 0.172, (10\times)0.2]\,. \tag{2}$$

Modeling tasks

1. Determine the quality factor Q and the resonance (normalized) frequency $f_{nor} = \text{period}/\lambda$ of the fundamental cavity mode for the structure *without* Si waveguide and *without* SiOx substrate, sweep N_{cav} from 2 to 12. We found this mode around $f_{nor} \approx 0.22$ to 0.23. (Optional: See if these results change when there is a SiOx substrate at a distance of $\text{BCB}_z = 1.0\mu\text{m}$.)

2. Add a Si waveguide (parallel with and at the center of the cavity) and a SiOx substrate with $\text{BCB}_z = 1.0\mu\text{m}$. Calculate Q in the following cases:

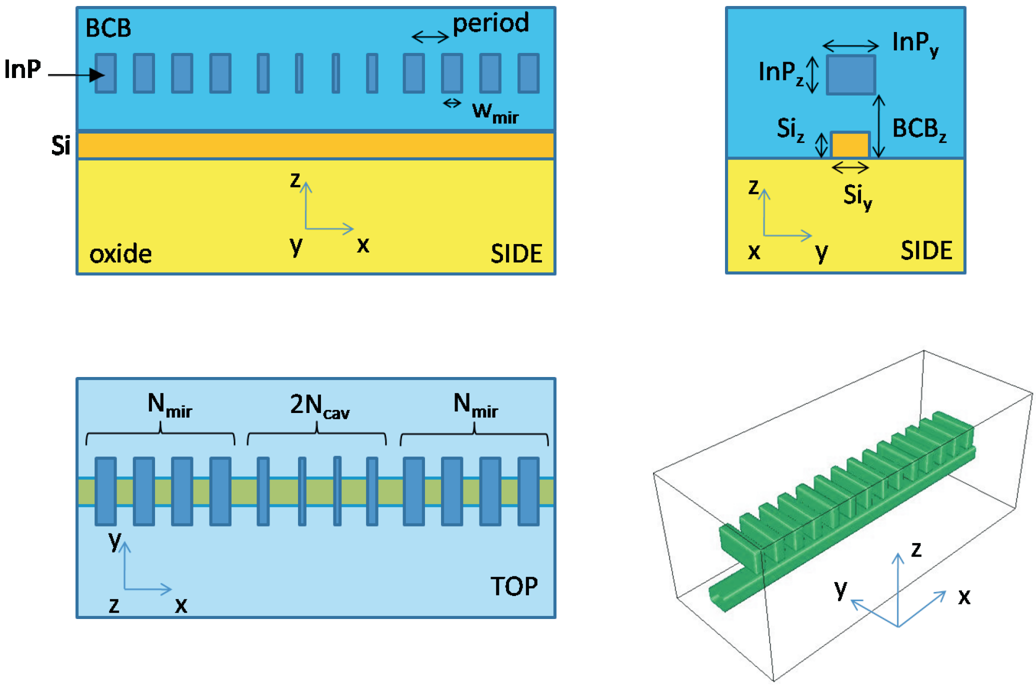

Figure 1: Geometry of the hybrid photonic crystal cavity device, coupled to a waveguide. The cavity is formed by the InP sections, the waveguide functions as input/output coupler. The 3D view only shows the Si and InP sections.

a) For each N_{cav} in $[5, 7, 10]$, do a sweep for Si_y from 0.1 to 1μm.

b) For each Si_y in $[0.2, 0.35, 0.5]$, do a sweep for N_{cav} from 2 to 12.

3. Again with the Si waveguide and SiOx substrate, take $N_{cav} = 5$. For each BCB_z in $[0.8, 1.2]\,\mu$m, do a sweep for Si_y from 0.1 to 1μm to obtain Q. (The case of $\text{BCB}_z = 1.0\mu$m is done in the previous task.)

4. Now we include a lateral offset (in the y-direction) Si_{off} for the Si waveguide with respect to the cavity. Take $N_{cav} = 5, \text{BCB}_z = 1.0\mu$m, and choose Si_y the value for which you obtained the smallest Q in task 2a (within the range $0.2 - 0.5\mu$m). Sweep Si_{off} from 0 to 1.5μm and obtain Q.

Simulation tools

It would be interesting to have a comparison between various tools and approaches. B. Maes has used FDTD (MEEP with harminv), where a point source was put at the center of the cavity. Similar approaches with other methods would be welcome (e.g. finite-element...). In addition, an approach where power is input from the Si waveguide could give a complementary picture (e.g. with 3D modal expansion).

If you do not find a 'reasonable' cavity mode for the first modeling task, contact B. Maes (bjorn.maes@umons.ac.be) to check if there is some problem with the parameters.

References

[1] Notomi, M., Kuramochi, E., and Taniyama, H. *Optics Express* **16**(15), 11095–11102 (2008).