Photonic crystal biosensing

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I. Introduction

Photonic crystals (PhCs) are structures exhibiting a periodic variation of the refractive index (see Figure 1). Due to this periodicity, light of certain wavelengths will interfere destructively with itself. We call this property a photonic band gap (named after a similar phenomenon found in electronics: the electronic band gap). The photonic band gap is illustrated in Figure 2.

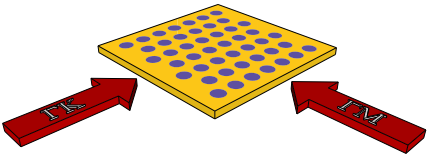

Figure 1. Photonic crystal with periodicity in 2 dimensions. Also displayed are the two main directions of light propagation: ΓM and ΓK.

The position and width of this band gap in PhCs strongly depend on the refractive index of the material in the holes. This fact can be exploited to create a biosensor: when the refractive index of the material in the PhC holes changes (e.g. because of binding between the PhC and the sample) we can measure the shift of the lower or upper band gap edge of the PhC (see also Figure 2 where the lower band gap edge shifts from λ_1 to λ_3 and the upper band gap edge from λ_2 to λ_4).

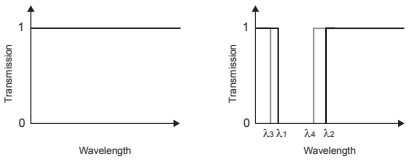

Figure 2. Transmission as a function of wavelength in a uniform lossless medium (left) and periodic lossless medium (right).

II. Increasing the sensitivity

In general, when designing a sensitive biosensor, one has to make sure there is as much interaction as possible between the light coupled into the chip and the sample one wishes to analyse - keeping in mind the technological limitations for eventual fabrication. In the case of a PhC biosensor this means that one wants to concentrate the electric field of the light in the holes of the crystal as this is where the actual sample to be measured is located.

There are three important guidelines to consider when designing a PhC biosensor: (1) the electric field of the second band mode is much more concentrated in the low refractive index regions compared to the first band mode; (2) the greater the diameter of the PhC holes, the more the field is concentrated in the holes; (3) the ΓM direction is more sensitive than the ΓK direction. These guidelines are the result of theoretical considerations and extensive simulations using both a plane wave expansion [1] and FDTD [2] method.

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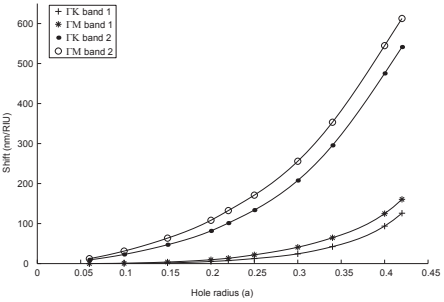

Figure 3. Silicon photonic crystal membrane (a photonic crystal structure based on refractive index confinement in the vertical direction) band gap shift as a function of hole radius for different combinations of ΓM, ΓK and lower and upper band gap edge. Thickness of membrane is 0.4 times the lattice constant.

(1) is a consequence of the variational theorem [3] which states that a light mode aims to minimize its electromagnetic energy functional. It can do so by concentrating itself in regions of high refractive index and by lowering the amount of spatial oscillations while remaining orthogonal to lower-frequency modes. Because the first mode - at a low frequency - is concentrated mainly in the high refractive index region, the second mode is forced into the lower refractive index region, at a higher frequency.

When looking at Figure 3, it can be seen that the sensitivity scales with the square of the hole radius. This agrees with what one intuitively would conclude since the volume of PhC holes also scales with the square of the radius.

The theoretical explanation behind the third guideline is based on field continuity conditions.

These three guidelines are illustrated in Figure 3.

A shift as high as 613 nm/RIU (Refractive Index Unit) has been calculated. This shift has been achieved when considering the shift of the upper band gap edge in the ΓM direction in a PhC membrane with a hole radius of 0.42 times the lattice constant. This agrees with all three beforementioned guidelines. The shift can be even higher when increasing the hole radius but due to technological constraints, this is not always possible.

III. Comparison with other biosensors

Here we make a comparison between several other photonic biosensors and the structure discussed in this paper. A more extensive overview of available biosensors and their characteristics can be found in [4].

Table 1. Comparison in sensitivity between photonic crystal biosensor and other biosensors.

Biosensor type	**Sensitivity (nm/RIU)**
Ring resonator	70
Slotted ring resonator	200
PhC with resonant defect	200
Photonic crystal	**613**
Surface plasmons	630

One can see from Table 1 that the PhC biosensor is only slightly less sensitive than a surface plasmon based biosensor but far more sensitive than ring resonator based ones or a PhC with defect.

IV. Conclusion

We have shown that it is possible to design a very sensitive photonic crystal biosensor when keeping in mind a few simple design guidelines. Sensitivities of 613 nm/RIU and more are possible (depending on technological limitations).

References

[1] Steven G. Johnson and J. D. Joannopoulos, Optics Express, Vol. 8, No. 3, 173-190, 2001.
[2] Ardavan Farjadpour et al, Optics Letters, Vol. 31, No. 20, 2972-2974, 2006.
[3] John D. Joannopoulos, Steven G. Johnson, Joshua N. Winn and Robert D. Meade, *Photonic Crystals - Molding the Flow of Light*, Princeton University Press, 2008.
[4] Xudong Fan et al, Analytica Chimica Acta 620 8-26, 2008.