Photonic crystal biosensor based on angular spectrum analysis

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There is and always will be a need for cost effective and reliable biosensors in many domains (e.g. medical, food industry, military). Apart from increasing sensitivity and detection limit, we must also consider ease of fabrication or implementation. In this work, we propose a novel photonic crystal based biosensor operating at a single frequency, contrary to resonance based sensors. Simulations have shown that for certain photonic crystal configurations there is a frequency range in which guided photonic crystal modes can couple to free space modes resulting in a Lorentzian shape in the angular spectrum. This Lorentzian peak can shift due to refractive index changes and sensitivities of 65° per refractive index and more are possible.

Introduction

Reliable and cost effective biosensors are in high demand in e.g. medical and biological sectors. Unsurprisingly, there is to this day still a lot of scientific output regarding optical biosensing [1].

In general there are two ways to develop an optical biosensor: making use of a fluorescent based or label-free sensing scheme. When using a fluorescent based biosensor the biomolecules that need to be measured are labeled with a fluorescent or radioactive marker. When illuminated, the labels emit a light- or radiowave where the intensity of the emitted radiation is a measure for the concentration. This labeling procedure is however quite complicated but there is an alternative: label-free sensing. In this case the biomolecules bond with receptor molecules attached to the sensor surface. As a consequence the refractive index near the surface will change, depending on the concentration of the biomolecules. Label-free sensors can also be used for bulk refractive index sensing (e.g. measuring salt concentrations).

Although already a lot of biosensor concepts in photonics have been investigated, we have come up with a novel sensing method based on photonic crystals (PhCs) [2]. Already quite a few PhC biosensors have been demonstrated: measuring the shift of a resonance peak induced by a defect in the PhC, monitoring the band gap shift or making use of guided resonances. In the first two cases, light is constantly guided in the plane of the PhC, in the latter case, the direction of the incident and outgoing light is out of the PhC plane. The sensor we propose here couples in-plane incident light (provided through a waveguide) out of the plane, like a grating coupler (see Figure 1).

Sensor concept

Simulations show that in photonic crystals, incident light from within a certain frequency region can be coupled out as a beam with a Lorentzian shape in the angular spectrum. We

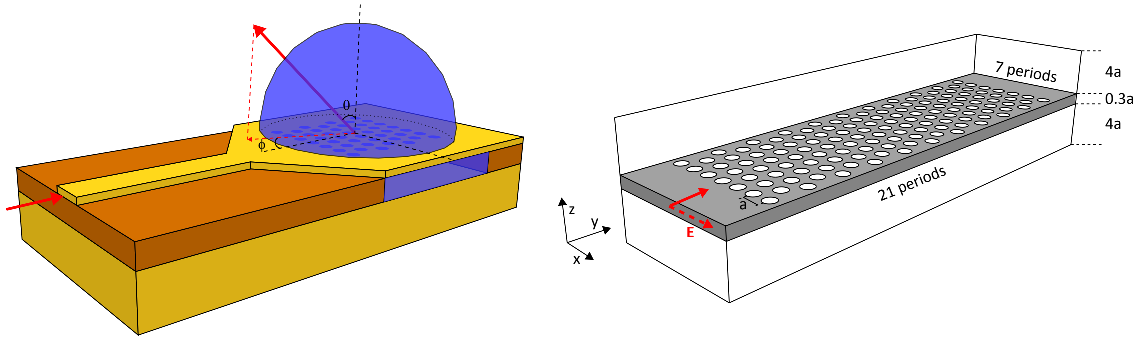

Figure 1: Light enters the PhC biosensor through a waveguide and is coupled to free space as a beam with inclination θ and azimuth ϕ (left). The simulated structure used for FDTD simulations is shown in the right figure. All sizes are normalized to the lattice constant *a*.

can see this in Figure 2 where the angular spectrum of the Poynting vector projected on the vertical direction for a certain frequency in that region is shown. The simulated structure is a 0.3*a* thick silicon PhC slab comprising holes of diameter 0.8*a* in a triangular lattice (where *a* is the lattice constant), excited with TE polarized light in the ΓM direction. The refractive index in the holes as well as that of the cladding layers above and below the PhC slab is set to 1.33, the refractive index of water. Simulations are carried out using a freely available FDTD method [3].

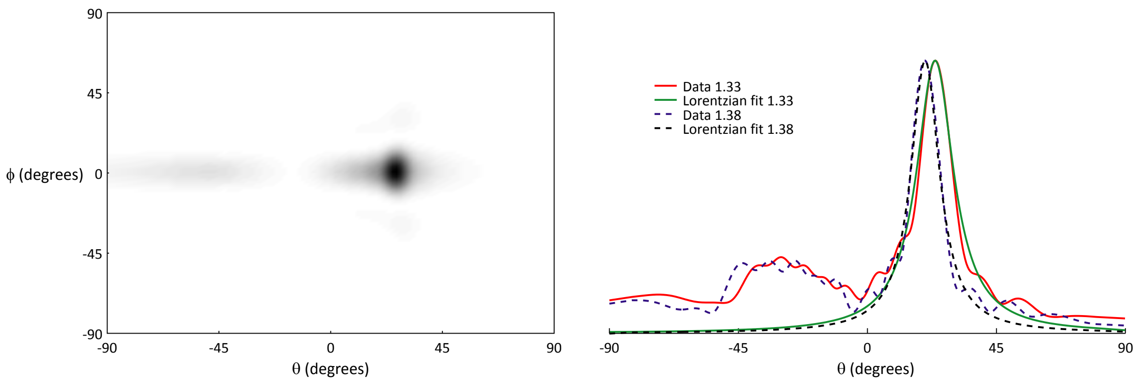

Figure 2: The angular spectrum (left) and cross-section at ϕ=0° (right) of the vertically projected Poynting vector of the proposed structure with a symmetric cladding (i.e. refractive index above and below PhC slab equals that of the holes) at normalized frequency 0.53488. A Lorentzian resonance shape is clearly visible.

We can distinguish the Lorentzian shape which we would expect to see due to the resonant coupling of guided modes to free space modes [4]. The angular position of this peak, which is dependent on the frequency, shifts due to changes in the refractive index which makes it interesting for sensing applications.

Simulation results for different cladding configurations

Depending on fabrication and implementation of microfluidics, the situation with respect to the refractive index in the neighbourhood of the PhC membrane will differ. Therefore, we have investigated the three main situations that can occur: only the refractive index in the PhC holes changes and above and below the membrane, there is only air (henceforth called the *no cladding* type); one cladding layer consists of air while the other has the same refractive index as that of the holes (*asymmetric cladding*) or both cladding layers and holes experience a change in refractive index (*symmetric cladding*). For each of these situations, we have performed simulations for several refractive indices which allows us to determine a shift per refractive index unit (RIU).
There are two ways to see a shift: by examining the angular spectrum at a fixed frequency using a spatial Fourier measurement setup [5] or by measuring the power at a given angle while scanning the frequency range. Both methods have been investigated and the results for the three cladding configurations are presented in Fig. 3. It should however be noted that the major advantage of the first method is that only a single frequency light source is needed in a fabricated device.

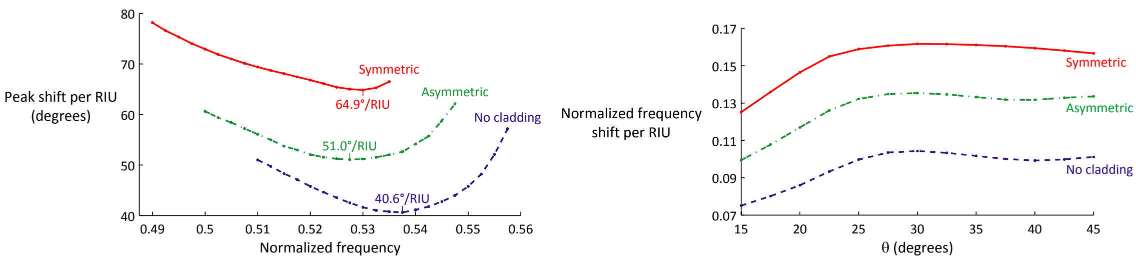

Figure 3: As expected, the shift for the symmetric cladding configuration is the highest in both approaches (left: monitoring the angular shift at a fixed frequency; right: measuring the frequency shift at a fixed angle).

Like we would intuitively expect, for both measurement methods, the *symmetric cladding* type is more sensitive than the *asymmetric cladding* configuration which is in turn more sensitive than the *no cladding* type. When measuring using the Fourier setup, it is advised to measure at a high frequency because a) the light is coupled out at an angle close to the PhC slab normal and is therefore easier to capture using a lens and b) it can be shown that the width of the resonance peak decreases with increasing frequency.
Using the other measurement method, we see for the three types a gradual increase in sensitivity with increasing angle until it becomes stable at about 25° and onwards.

Conclusions

We have devised a new photonic crystal based biosensor concept based on the coupling of guided to free space modes. The major advantage of this device over resonance based sensors (e.g. ring resonators) is that it is able to operate at a single frequency. With a simulated sensitivity of 65° per RIU and more, the proposed device performs better than a SPR sensor in the angular regime (i.e. operating at a single wavelength) [6]. Furthermore, when fabricating the device there is no need for a metal deposition step or a coupling prism.

If a broadband light source is available, it is possible to operate the device in a reciprocal way by measuring the peak frequency shift at a fixed angle.

Acknowledgments

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