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High performance photonic biosensors based on periodic configurations

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ABSTRACT

Periodic photonic configurations as photonic crystals (PhCs) and subwavelength grating (SWG) waveguides are gaining a renewed interest for the development of biosensing structures. By performing a proper design, these periodic configurations allow a significant sensitivity increase while keeping a compact footprint, what is achieved by exploiting concepts such as the slow-wave effect, the increase of the light-matter overlap or the interference of dispersion engineered modes.

Keywords: photonic sensors, periodic structures, photonic crystal, subwavelength grating, integrated photonics

1. INTRODUCTION

Photonic technology has raised a great interest for the development of high-performance analysis devices due to the significant advantages that it provides, as for example high sensitivity, compactness and high integration level, short time to result, label-free detection, and use of very low sample volumes, among others¹⁻³. These advantages will allow deploying compact and low-cost analysis systems able to simultaneously detect hundreds/thousands of analytes in few seconds/minutes using simply a couple of drops of the sample to be analyzed. However, despite being very high, the sensitivity provided by photonic technology is sometimes not enough to detect very low concentrations of the target analytes or to detect target analytes with a very low molecular weight. Within this context, periodic photonic configurations as photonic crystals (PhCs) and subwavelength grating (SWG) waveguides are gaining a renewed interest for the development of biosensing structures. By performing a proper design, these periodic configurations allow a significant sensitivity increase while keeping a compact footprint, what is achieved by exploiting concepts such as the slow-wave effect, the increase of the light-matter overlap or the interference of dispersion engineered modes. Additionally, the combination of these configurations with other concepts like the use of porous materials, the use of amplified biorecognition schemes or the use of microfluidic concentration elements can lead to unprecedented sensing performances. In this work, we present different approaches based on periodic structures being developed in our group for increasing the sensitivity of nanophotonic-based sensing devices.

2. PHOTONIC BANDGAP SENSING STRUCTURES

One of the main properties that has been exploited in periodic dielectric configurations is the possibility to obtain spectral regions where the propagation of optical modes is forbidden, known as photonic bandgaps (PBGs). These structures can be used for sensing applications by monitoring the spectral shift of these PBGs when the refractive index of the surrounding environment is modified, for example, due to the binding of the target analytes to the surface of the structure. Another interesting phenomenon occurring in these PBG periodic structures is the appearance of the so-called slow-wave effect for the PBG edge modes, which translates into a higher sensitivity due to the higher interaction with the surrounding environment that is produced due to the group velocity reduction. This sensitivity increase allows reducing the footprint of the structure in comparison with other photonic sensing structures typically used as for example interferometric configurations.

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Although periodicity in several dimensions can be considered for the creation of these PBG structures, periodicity in the propagation direction can simply be considered when working with guided wave configurations. In this way, their design and fabrication can be simplified. For example, 1D PBG structures can be created by periodically introducing transversal elements in a single mode waveguide, as it is depicted in Figure 1a. We have used these 1D PBG sensing structures for the detection of different types of analytes, including antibodies, proteins, enzymes and oligonucleotides⁴⁻⁸. Figure 1b shows experimental results obtained for the detection of a 35-mer target oligonucleotide⁴. In this experiment, silicon 1D PBG structures were biofunctionalized with molecular beacon (MB) probes, leading to a very high sensitivity towards the detection of these short length target oligonucleotides, obtaining spectral shifts of the PBG edge even above 1 nm. These shifts are even more than one order of magnitude higher than those typically obtained using other photonic sensing structures as ring resonators for the detection of similar targets. On the other hand, Figure 1c shows experimental results obtained with a similar silicon 1D PBG structure for the detection of increasing concentrations of thrombin, where we have been able to observe spectral shifts for concentrations below the nM level⁸.

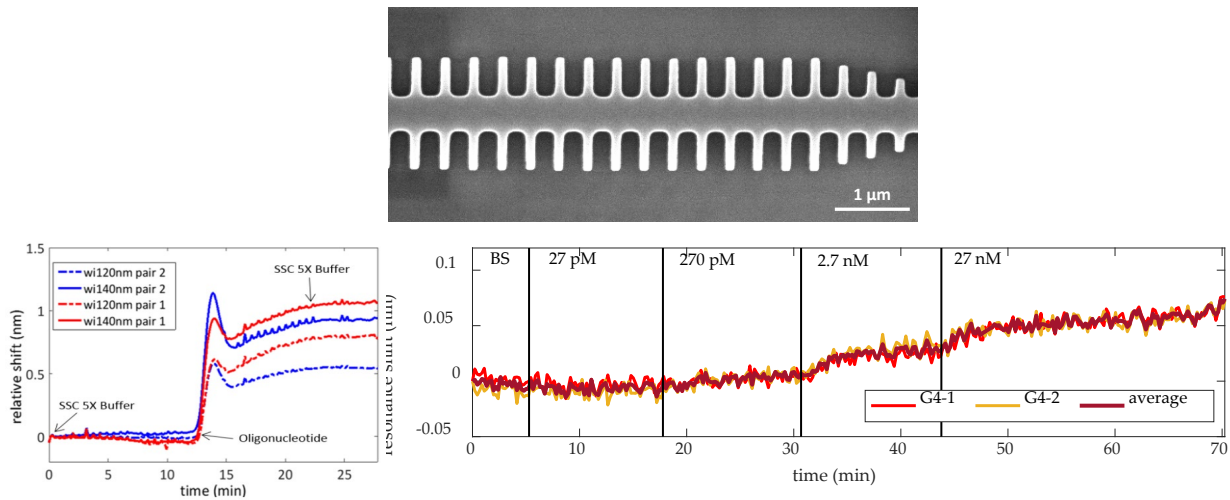


Figure 1. Scanning electron microscope (SEM) image of a fabricated silicon 1D PBG structure. A linear taper is created at its accesses to improve the coupling. (b) Evolution of the PBG edge position for four 1D PBG sensing structures with different parameter w_i (width of the transversal elements) being biofunctionalized with specific MB probes. The 1D PBG sensing structures respond to the presence of the target oligonucleotide when it is flowed over them. (c) Evolution of the PBG edge position towards increasing concentrations of thrombin for two 1D PBG sensing structures being biofunctionalized with thrombin binding aptamers as bioreceptors.

3. BIMODAL SWG INTERFEROMETRIC SENSORS

A way to increase the sensitivity when using evanescent wave based photonic structures is by using interferometric configurations, as for example Mach-Zehnder interferometers (MZIs). However, this type of sensing configurations requires two long optical paths and other additional structures as signal splitters to carry out the sensing, making their integration complicated in small devices. In order to reduce the size of interferometric sensors, novel configurations where the phase shift is produced by different optical modes propagating in the same waveguide have been proposed. This is the case of the so-called bimodal waveguide sensors⁹.

On the other hand, another type of photonic configuration that is rising a great interest in the last years is SWG waveguides¹⁰. In this waveguide configuration, the typical solid-core dielectric waveguide is replaced by a periodic structure whose periodicity is considerably smaller than the wavelength of the propagating wave; this makes that the light considers that periodic structure as a homogeneous medium with an effective refractive index given by the combination of the dielectric elements and the “empty” spaces between them. In terms of sensing applications, the fact that SWG structures also comprise these “empty” regions makes that the optical field propagating through the waveguide can interact directly with the medium present in those regions (i.e., not only the evanescent field used for sensing), thus proving a sensitivity increase.

In this context, we have proposed a novel type of photonic sensor based on the combination of these two concepts: the creation of bimodal interferometric sensors using SWG structures¹¹⁻¹². This novel combination gives rise to significantly higher sensitivities than those already demonstrated when using these two concepts by separate, as the fact of having a higher interaction with the surrounding medium in SWG structures will be added to the great benefits of interferometric sensing. Additionally, the dispersive behavior of modes in periodic structures also allows to further increase the sensitivity of the proposed sensing structure. Figure 2a schematically depicts the proposed configuration, where a SWG structure having the required width to support one even and one odd mode is created. The interference of both modes at the output single mode waveguides provides a clear interferometric response, as it is depicted in Figure 2b, which is shifted towards shorter wavelengths when a refractive index increase is produced in the surrounding environment. Using this interferometric approach, we have experimentally measured extremely high sensitivities up to 2270 nm/RIU (Refractive Index Unit) for a purely dielectric structure with a length of 124.8 μm (480 periods), as shown in Figure 2c.

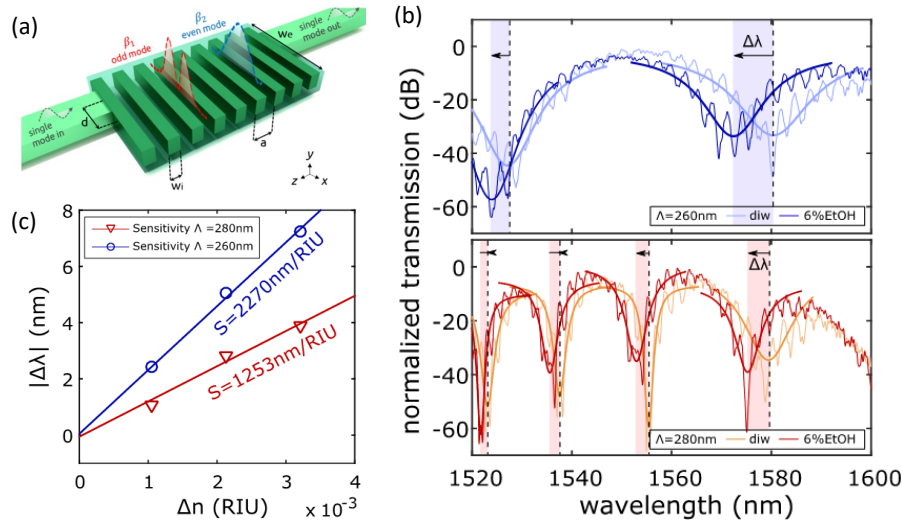


Figure 2. (a) Schematic representation of the proposed bimodal SWG interferometric sensor. The access single mode waveguides are shifted from the SWG axis to excite both the supported even and odd modes in the structure. (b) Experimental normalized transmission spectra for two SWG interferometric sensors of period $\Lambda_1=260\text{nm}$ (upper blue graph) and $\Lambda_2=280\text{nm}$ (lower red graph). The spectrum is shifted towards shorter wavelengths when the refractive index of the surrounding medium is increased (change from deionized water to a 6% of ethanol). (c) Sensitivity curves for the two configurations of SWG interferometric sensors considered in the study.

4. BIMODAL PBG INTERFEROMETRIC SENSORS

From the benefits previously observed when using PBG structures and bimodal interferometric configurations for the development of nanophotonic sensors, our next step is combining both concepts in order to increase the sensitivity and reduce the footprint even more. To this aim, we have designed 1D PBG structures as those previously introduced in section 2 in order to have a bimodal behavior for certain wavelength range. As depicted in Figure 3a, the interaction between the different modes of the PhC results in the appearance of anti-crossing points where flattened bands are obtained. For these bands, spectral regions where two different modes having different propagation constants can be obtained (see Figure 3b). By properly designing the periodic PBG structure, a very high difference between the group index of both modes can be obtained if one of them is in the slow-wave regime, thus leading to a dramatic increase in the phase sensitivity of the interferometer.

This configuration has been fabricated (see Figure 4a) and its sensing performance experimentally characterized. Figure 4b depicts the phase sensitivity of the bimodal PBG interferometer normalized to a length of 1 cm. We can observe that a dramatic increase in the sensitivity is obtained for shorter wavelengths. This wavelength range corresponds to the spectral region where the 2nd order mode (depicted with red color in the bimodal region in Figure 3a) approaches the edge of the Brillouin zone and becomes slow wave, leading to a significant increase of its group index. This increase of the group index can also be observed from the measured transmission spectrum in Figure 4c, where interference fringes

become narrower and more grouped as we move towards shorter wavelengths. Experimental sensitivities of 10^4 2π rad/RIU \cdot cm have been obtained using this bimodal PBG interferometric structure, which means an improvement by a factor of more than 10 with respect to traditional MZI configurations and around 7.5 for slot-based MZIs and for silicon nitride bimodal waveguides.

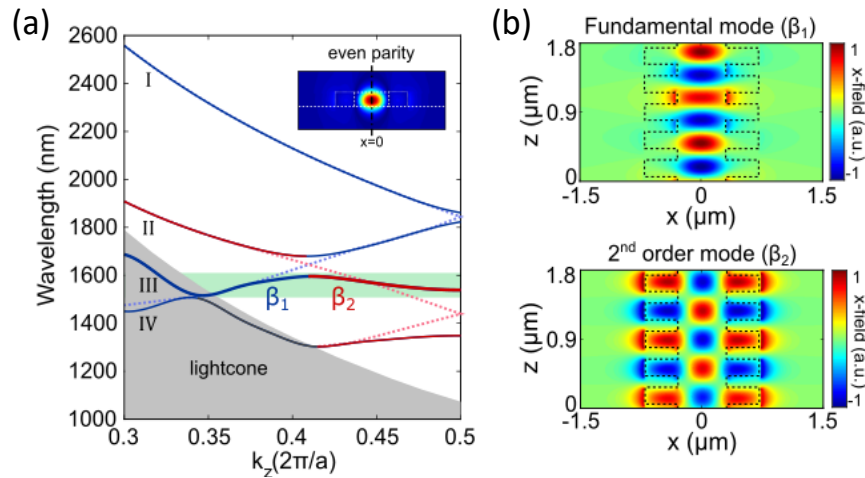


Figure 3. Dispersion diagram of the 1D PBG structure showing the x-even parity bands for the TE-like polarization. The green shaded area depicts the bimodal region created in the proposed structure, where two modes with two different propagation constants are excited. (c) Real part of the electric field x-component in the xz plane for $y=0$ for the two modes excited in the bimodal region. The black dashed line represents the geometry shape of the silicon 1D PhC structure.

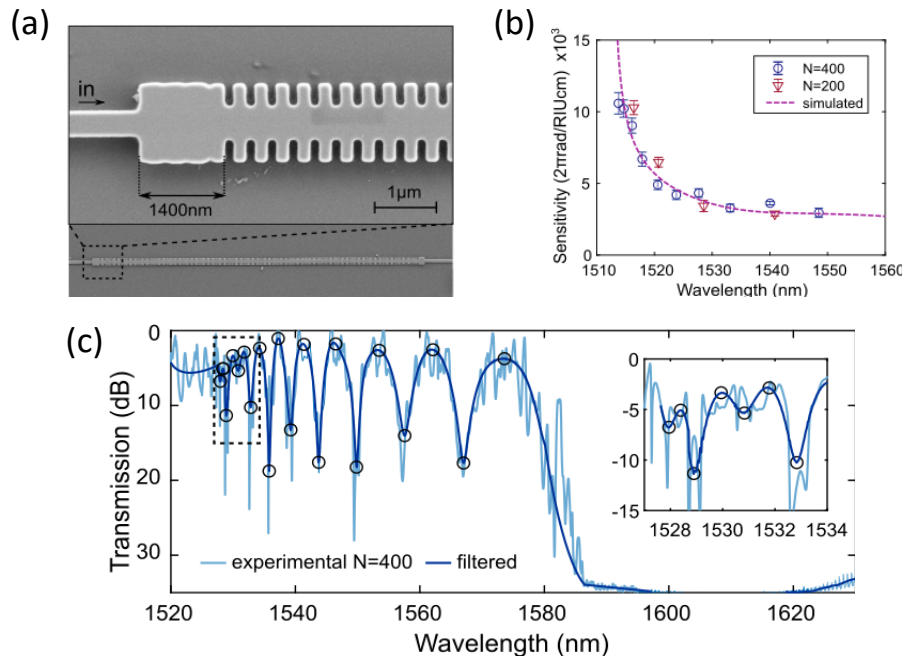


Figure 4. (a) SEM image of the fabricated bimodal PBG interferometric structure. An access rectangular taper is created to properly excite both modes. (b) Length-normalized phase sensitivity experimentally obtained for two bimodal PBG interferometric sensors having a different number of periods ($N=200$ and $N=400$). Pink dashed line represents the theoretically predicted sensitivity curve. (c) Normalized transmitted spectra for the bimodal PBG interferometric structure having $N=400$ periods (length $148\ \mu\text{m}$). Light color represents the raw experimental data, while dark color represents the filtered signal without the Fabry-Perot ripple created in the photonic circuit cavities. Constructive and destructive interferences are marked with black circles in both graphs. Insets depict a close up view of the transmission spectrum in the slow light region.

5. CONCLUSIONS

By using periodic structures working in the PhC or in the SWG regime it is possible to obtain a significant performance improvement when developing photonic sensing devices. Characteristics such as their dispersive behavior, the slow-wave effect or the delocalization of the field into the surrounding medium allows increasing their sensitivity and reduce their size. This performance can be significantly further improved when periodic structures are combined with other concepts, as it is the case of interferometry. From the results obtained, we demonstrate that the combination of PhC/SWG structures and bimodal interferometry opens the door to the creation of ultra-sensitive and ultra-compact photonic sensing devices. We expect that the broad design possibilities of periodic structures (i.e., different shapes, periodicities, dimensions, materials, defect types, etc.), together with the combination with other concepts such as the use of porous materials¹⁴, can lead to novel configurations having even better sensing performances.

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