Education and Training in Optics & Photonics Conference 2021

Defining Sensitivity of Integrated Optical Biosensors: A Multidisciplinary Lesson Approach

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Abstract: Integrated optical biosensors based on ring resonators play a crucial role for future point-of-care-diagnostics. On this subject, a multidisciplinary lesson is designed to provide students an understanding of waveguide sensitivity, device sensitivity and overall sensitivity.

1. Introduction

Optical sensors in photonic integrated circuit (PIC) technology have great potential for cost-effective disposable sensors with various applications in environmental monitoring, food analysis and point-of-care-testing [1,2]. Such sensors have the potential for the simultaneous analysis of various substances and physical parameters such as temperature [3]. Further, they provide rapid results within minutes and the direct translation of the optical into an electrical signal by using a chip-integrated photodiode allows reliable and secure data transfer, employing modern communication protocols. One main advantage, however, is the miniaturization of the complete sensor system. This includes the light source, sensor element and electronic readout, which gives perspectives to mobile and lab-on-a-chip applications.

Students and young scientists in this multidisciplinary environment need not only a good understanding of the working principals of the optical sensor but also an understanding of the definition of sensitivity in this context.

In this work, a multidisciplinary lesson plan is modeled around the guiding question ”What is the difference between waveguide sensitivity, bulk sensitivity and surface sensitivity”. The lesson is designed within the framework of a Master’s course in photonics at the Technical University of Applied Sciences Wildau, Germany. As specific example we use microring resonator biosensors.

2. Physical background and working principle

The working principle of micro-ring resonators as optical sensor is based on a refractive index change. At this point, we should distinguish between two cases. First, if the refractive index of the surrounding material changes, we speak about refractive index sensing in bulk material or surface sensing in case of specific detection of molecules at the surface of the waveguide. Second, if the refractive index of the optical waveguide is changed, we speak about thermal or stress sensing, depending on either the refractive index change originates from a temperature change or from the applied stress inside the silicon waveguide, respectively. Temperature sensing is highly efficient in silicon-based PICs due to its large thermo-optical effect. In all aforementioned cases, the detection principle relies on the change of the effective refractive index of the optical waveguide which causes a change of the resonance wavelength:

$$\Delta\lambda = \frac{\lambda_{res}}{n_{eff}} \Delta n_{clad} \tag{1}$$

Here, λ_{res} refers to the resonance wavelength, Δn_{clad} represents the cladding refractive index change which is similar to the refractive index change of the fluid. We assume a negligible dispersion of the group index and, therefore, we can use the effective refractive index n_{eff}.

From Eq. 1 it is apparent that our goal is to design an optical sensor that can translate a low change in refractive index Δn_{clad} to a large resonance wavelength shift $\Delta\lambda$.

3. Optical waveguides

In contrast to more traditional free-space optical sensors, integrated photonic sensors based on MRR use light that is confined inside an optical waveguide. As opposed to optical fibers, an integrated optical waveguide has a rectangular shape due to the fabrication. In general, three waveguide structures are intensively studied over the

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last two decades. The most important difference is their geometry that influences both, the waveguide loss and sensitivity. It is crucial to find a trade-off for this.

4. Waveguide, device and overall sensitivity

The interaction of the guided light with the surrounding medium is not only described by the field confinement factor but also by the waveguide sensitivity. It can be shown that a higher field confinement inside the cladding material, which is in fact the fluid, increases the waveguide sensitivity. Since the effective refractive index reflects the light propagation inside a waveguide, the waveguide sensitivity is defined in different ways, depending on the sensing mechanism, i.e. chemical bulk sensing or label-free surface sensing. In principle, the waveguide sensitivity is evaluated by

$$S_{wg} = \frac{\Delta n_{eff}}{\Delta n_{clad}}, \tag{2}$$

where Δn_{eff} represents the effective refractive index change and Δn_{clad} the change of the cladding refractive index.

The device sensitivity for a microring resonator is the so called ring resonator sensitivity S_{rr}, which depends not only on the waveguide geometry and, therefore, a definition defining the ring resonator sensitivity is given by

$$S_{rr} = \frac{\Delta \lambda_{res}}{\Delta n_{eff}}. \tag{3}$$

Taken both definitions into account, we get the overall photonic device sensitivity defined by

$$S = S_{wg} S_{rr} = \frac{\Delta n_{eff}}{\Delta n_{clad}} \frac{\Delta \lambda_{res}}{\Delta n_{eff}} = \frac{\Delta \lambda_{res}}{\Delta n_{clad}}. \tag{4}$$

Figure 1a shows a general overview of the multidisciplinary lesson plan and Figure 1b a specific example of a microring resonator biosensor.

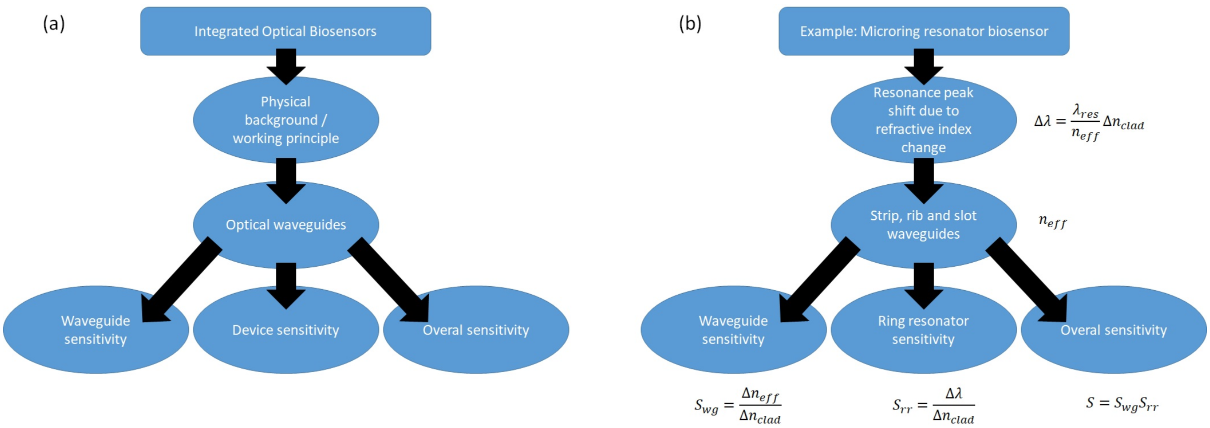

Fig. 1. Overview of the multidisciplinary lesson plan: General approach (a) and specific example of a microring resonator biosensor (b).

5. Conclusions

We have designed a multidisciplinary lesson around the guiding question. An approach is provided to teach students in a Master's course. This approach begins with a basic understanding of the working principle and ends by answering the guiding question. A specific example of a microring resonator biosensor is provided.

References

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