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General

A compact optical chip for refractive sensing based on cut-off enhanced modal coupling changes

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ABSTRACT

A novel type of integrated optical sensor has been evaluated theoretically. The sensing is based on the large effect of the refractive index of the measurand (generally a liquid) to the mode profile of a guided mode close to the cut-off. A special type turns over into a leaky mode-based sensor. The sensor has small size and is simple to fabricate. For the SiON technology-based structures used as a vehicle for the evaluation, a resolution of the refractive index in the range of 10^{-6} RIU has been achieved; however, with an operation range around a certain working index of $\approx 2 \times 10^{-4}$ RIU only. This working index can be shifted to any desired value, within a certain range, by appropriately choosing the geometrical and material parameters. Because of technological tolerances, for practical operation, read-out based on wavelength scanning is required. The sensor can be used especially as an alarming sensor.

1. Introduction

During the last decades, many integrated optical (IO) sensors have been proposed, their potential has been investigated both theoretically and experimentally and some of them have been commercialized even. These developments have been described amongst others in recent review papers [1–5]. The high sensitivities and excellent resolutions obtained in various integrated optical sensing systems, their potential of integrating many sensors as an array on one single optical chip and the application of production methods already developed in IC technology make these sensors very suited for measuring a refractive index (change) with high resolution in multi-sensing arrays.

In these refractive IO sensors, a large variety of optical principles has been applied, such as interferometry [6–9], optical resonance (ring resonators) [10,11] grating coupling [12,13] and surface plasmon resonance (SPR) [14–17]. In all of these, a change of a refractive index brings about a change of the propagation speed of a guided mode which is generally expressed in terms of changes of the effective index N. They differ, however, in the way in which these changes are transduced into changes of the optical output power.

These principles enable homogeneous sensing at a resolution (the smallest change δn of the refractive index n which can be monitored) in the range of 10^{-5}–10^{-8} RIU. The best resolutions, δn being in the range 10^{-7}–10^{-8} have been reported for interferometric systems [7–9] and for phase-sensitive SPR sensing systems [17]. These excellent resolutions make these systems very suited for measuring extremely small concentrations (down to picomoles) of chemical compounds in gasses or solutions. For the latter, generally thin chemo-optical interface layers are introduced in which, e.g. receptors selective for the analyte molecules have been incorporated. It has to be noted that the resolution depends not only on the integrated optical structure implemented on an optical chip, but also on the quality of the peripheral (opto-electronic) equipment such as a light source, temperature control and a detection system and also on the sensing conditions.

However, not all applications require such extremely good resolutions and it was and it is worthwhile to develop IO sensing systems with lower quality of resolution, in particular, if these are simpler and hence cheaper: good examples are the grating coupling-based devices with resolutions δn in the order of magnitude 10^{-6}, which are already commercially available [18,19].

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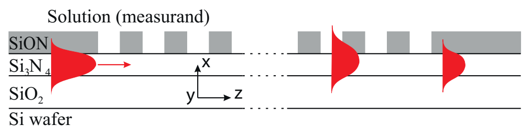

Fig. 1. Schematic longitudinal cross-section of a periodic SWG sensor containing about 2000 periods of length 20 μm.

In a second type of refractive IO sensing systems, it is not the change of N but the change of mode profiles which is utilized [20,21]. They show resolutions δn in the order of magnitude 10^{-6}.

In spite of all good results obtained up to now, it is interesting to investigate the potential of new types of refractive IO sensors, interesting both from application point of view (price/performance ratio) and by reasons of scientific curiosity. Such a novel type of sensor is proposed in this paper and results of its theoretical evaluation are presented. It is a refractive sensor of the second type, so based on resulting changes of mode profiles. It is a special type of the segmented waveguide sensor (SWG), we have reported in [20]. The structure of the novel sensor is simpler, just as its production technology. For an optimized sensor, a resolution $\delta n \cong 10^{-6}$ has been calculated.

The rest of the paper is organized as follows: in Section 2, the sensor principle is given. A simple sensor structure is worked out in Section 3. Based on an analysis of the performance of this structure, a modified structure has been designed showing calculated resolutions down to 10^{-6} (Section 4). In Section 5, results of a preliminary experiment are given. Results are discussed in Section 6 and finally a summary is given in Section 7.

2. Sensor principle

The chemical sensor proposed and evaluated in this paper can be considered as a special form of the segmented waveguide sensor (SWG), we have reported in [20]. The basic IO structure of this earlier SWG sensor, which has been made by SiON technology, is given in Fig. 1: a mono-modal waveguiding structure, which consists of an alternating series of two different sections, the segments: the sensing segments, in which both the speed and the field profile of the propagating mode are sensitive to the refractive index of, e.g. the solution to be monitored and the passive segments, where these modal characteristics are insensitive to the measurand. The segmentation can be periodical as in the well-known grating structures, but in contrast to the common grating sensors [12,13] it is not the change of a modal propagation velocity which is utilized but the change of the mode profile in the sensing segments. Because at the transition of two subsequent segments, the transfer of guided mode power from the one segment to the other is governed by the overlap integral of both mode profiles, a change of the refractive index of the solution will finally result into a change of the transmittance of the segmented waveguide. However, as already argued in [20] this picture is too simple: in a deliberately segmented structure, the guided mode power lost at a transition by conversion into a diverging free space beam can be partly reconverted into guided mode power at next transitions. At segment lengths in the micrometer range, the phase differences between the free space beams and the guided mode arriving at next transition are very small leading to almost completely constructive interference. So the effective modal power loss at each transition will not be very high. But nevertheless the large number of transitions in such a device lead to useful transmission changes and at a segmented waveguide length of 4 cm over a large refractive index range resolutions down to $\delta n = 10^{-6}$ RIU could be demonstrated [20,22].

Starting from this principle, we designed a segmented structure, where the power transfer at the transitions is made very sensitive

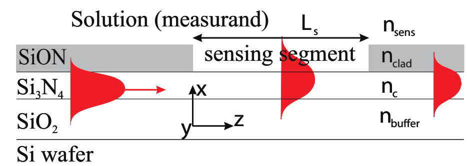

Fig. 2. Longitudinal cross-section of the considered slab structure of an SWG sensor consisting of three segments.

to the refractive index of the measurand by ensuring that in the sensing segments the mode is close to the cut-off condition. In this state, a small refractive index change can lead to a large change of the mode profile. Recapture can be reduced by having larger segment lengths and for the model study we focused on the simple waveguide structure built from a single 2 cm long sensing segment only, adjacent to two short passive segments. In the paper, it will be shown that theoretically in such type of structure again resolutions δn around 10^{-6} RIU can be achieved.

3. Theoretical evaluation of a first sensor structure

The theoretical analysis will be done at vacuum wavelength $\lambda_0 = 632.8$ nm assuming IO structures realized by the SiON technology, which we have available in our laboratory [23,24]. In these structures, the layer stacks are built from a SiO_2 buffer layer, made by thermal oxidation of a Si wafer ($n_{buffer} = 1.452$), a SiON core layer made by PECVD ($n_c = 1.920$) and a SiON cladding layer having the lowest refractive index value producible by PECVD, $n_{clad} = 1.472$. Although practical sensors will be realized as waveguiding channel structures, for reasons of simplicity the theoretical analysis will be directed to slab structures. All qualitative conclusions can be generalized to channel structures, while for ridge waveguides with small etching depth the quantitative results can be considered as fair approximations.

The principle of the sensor structure is given in Fig. 2. In the sensing region, the cladding material is etched off completely by RIE inspired by the idea that in that way the highest sensitivity of the guided mode profile for changes of the refractive index of the solution can be obtained. For defining appropriate values of layer thicknesses, a slab mode solver has been applied.

Assuming cladding and substrate layer thickness to be infinite, support of zero-order modes only is ensured for core layer thicknesses below 0.27 μm. The lower the thickness of the high index core layer, the larger the part of the modal power that propagates through the solution in the sensing segment and, as might be expected by intuition, the larger the sensitivity to solution's refractive index changes. On the other side, the thinner the core layer, the thicker buffer layer and cladding layer in the passive segments are required, which leads to larger production times. As a compromise, a thickness of 40 nm has been chosen, a thickness which guarantees mono-modality and also allows for efficient fiber to chip couplings in the channel type waveguides which are foreseen in final sensor systems. For reducing the modal loss due to absorption by the Si wafer and radiation into the wafer to about 0.1 dB/cm, a buffer layer thickness of the 2 μm is suited. For safeguarding the guided mode in the passive segments against any influence of the solution, a cladding layer thickness of 3 μm shows to be sufficient.

The length of the sensing section is chosen to be 2 cm in order to keep recapture effects small, as was indicated by some preliminary calculations. On top of the passive segments, a flow through glassy cuvette will be placed through which the solution to be monitored is flown. Preferentially, the cuvette is made of a glass type having a refractive index somewhat higher than the index of the cladding layer for removing guided cladding modes which may be generated unintentionally either at the input of the waveguide or by the free