The Segmented Waveguide sensor: principle and experiments

Joris van Lith, Paul.V. Lambeck, Hugo.J.W.M. Hoekstra, Rene. G. Heideman
Lightwave Devices Group, MESA+-institute, University of Twente, P.O. Box 217,
7500 AE Enschede, the Netherlands
J.vanLith@el.Utwente.nl

A novel type of chemo-optical sensor has been designed, fabricated and characterized. The sensor is simple to fabricate and it shows a resolution of the chemically induced refractive index changes better than 5.10^{-7}

Keywords: Segmented waveguides, Sensing, guided-wave optics

Introduction

Integrated optical sensor systems have a large potential to be small, very sensitive and relatively cheap [1]. A novel type of sensor, in which chemically induced changes of refractive index are read out as index dependent losses, has been investigated. This sensor has low demands on the technology and on the quality of the light source, but still enables high resolution. Using standard peripheral equipment a resolution of 5.10^{-7} should be feasible. The sensor can be used as an on/off alarm sensor or for continuous measuring. In this paper first the principle will be treated, followed by presenting the design, the realization, the characterization and conclusions.

Device principle

In figure 1 a longitudinal cross-section of the sensing part is depicted: a ridge type wave-guiding channel consisting of two types of segments: segments with SiON as cladding and segments with a sensing material as cladding. The sensing material is a chemically active material whose refractive index depends on the concentration of a specific chemical compound. A guided mode is launched into the first segment of the waveguide. Due to the difference in field profiles of both types of segments not all guided mode power launched into this segment will be transferred to the guided mode of the adjacent segment. At the transition radiation will be generated. The amount of lost guided mode power of course depends on the difference in refractive index Δn between SiON and the sensing material and hence is a measure for the concentration of the measurand. At one transition the chemically induced loss of guided mode power is very small; however, with a few thousand transitions a quite sensitive sensor can be obtained.

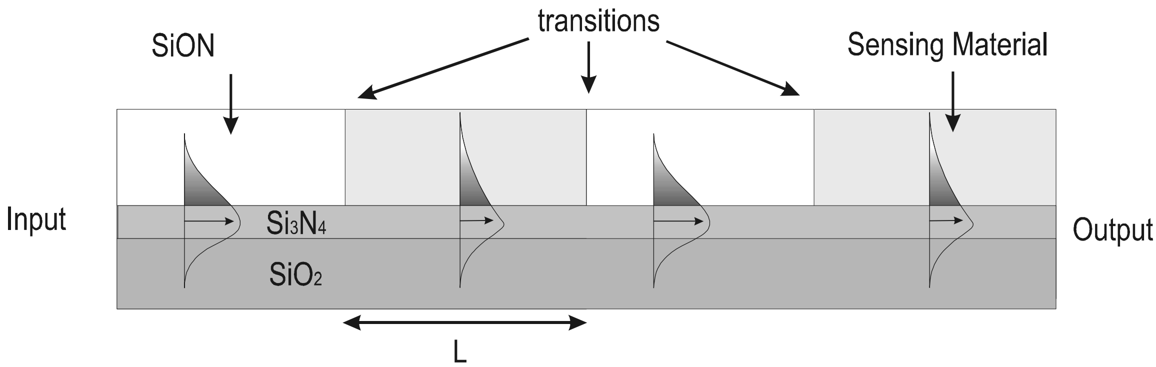

Figure 1. Longitudinal cross-section of the sensor

If there is no difference in refractive index between SiON and sensing material, then no radiation will be emitted: this state is called the working point. The index of the SiON cladding layer can be tailored to that of the sensing material [2], allowing e.g. to define the alarming point of an alarm sensor

Part of the power radiated out at one transition can be transferred to guided modes at the next transition. Depending on the phase difference, there can be constructive or deconstructive interference at the transition between the electrical fields of the original guided mode and the radiation coupling back into the guided mode. The distance L between two transitions mainly determines this phase difference and is thus an important design parameter. Note that the larger the segment length, L, the less radiation is coupled back into the guided mode. Although not required, for simplicity reasons we have chosen for a periodic structure. Note however that the principle works for any distribution in L and that the nature of the distribution itself is a design consideration.

Design

For the design of the Segmented Waveguide Sensor (SWS) it is important to have a simulation method that can handle radiation very well. Three methods have been used: a finite difference beam propagation method [3], a bi-directional eigenmode propagation method [3] and a spectral decomposition method [4,5] all methods being 2D-ones. Unfortunately there were none 3D simulation tools available that could handle the very thin Si_3N_4 core layers, applied in the sensors. The vast majority of the radiation is expected to be directed into the transversal direction, so using 2D methods is probably an acceptable approximation. Results of all methods agreed very well with each other. The spectral decomposition method is very useful for gaining extra insight because in this method the influence of the waveguide structure and the segmentation are expressed as independent factors within the power transfer function.

In the design the sensitivity S, is optimised. This sensitivity is defined as $S = \partial\eta / \partial\Delta n$ where η is the functional loss expressed in dB/mm. So the sensitivity is defined for 1 mm of sensor length and Simulation results show that the functional loss is in approximation a quadratic function of Δn around $\Delta n = 0$.

The two most important design parameters are the thickness of the core layer and the segment length L. The core layer has to be thick enough to guarantee confinement of the modal field in the a layer stack of acceptable thickness (about 5 μm). However it appeared that a thicker core layer results in a decrease in sensitivity while the optimum L will shift towards small values (<2 μm). Such small L values give problems with the fabrication. A core thickness has been chosen that copes optimally with both effects. At this core thickness the waveguide is single mode in the transverse direction and only guides TE light. The sensor has been designed for a 850 nm wavelength because at this wavelength there are cheap commercial light sources available.

Fabrication

The SiO_2 optical buffer layer was grown by thermal oxidation of the silicon wafer. Then the Si_3N_4 core layer was deposited using low-pressure chemical vapor deposition and the channel waveguides were wet-etched using BHF. After that an index matched SiON cladding was deposited using plasma enhanced chemical vapor deposition. The SiON cladding was etched using reactive ion etching. After the deposition of the core layer V-grooves were etched in the wafer for easy fiber-to-chip coupling [6]. In figure 2 a SEM picture of the sensor is shown. In the middle the Si_3N_4 channel waveguide can be seen. On top of the waveguide there are the blocks of the SiON cladding. On top of this structure the sensing layer can be spun, or the structure can be submerged into a liquid. In table 1 the relevant parameters of the fabricated SWS are listed.

Table 1. Parameters of the fabricated SWS

Layer	Thickness	Index (850 nm)
SiO_2	2.8 ± 0.1 μm	1.453 ± 0.001
Si_3N_4	58 ± 0.1 nm	1.996 ± 0.001
SiON	2.00 ± 0.02 μm	1.520 ± 0.001

	Property	Value
SiON	Under-etch	0.5 ± 0.1 μm
SiON	Transition angle	53 ± 5°
Si_3N_4	Channel width	6.9 ± 0.1 μm

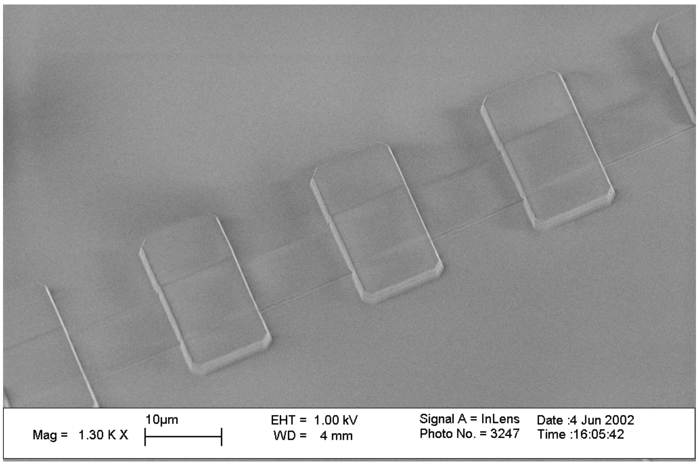

Figure 2. SEM photo of SWS

Characterization and analysis

To demonstrate the principle of the sensor and to check the validity of the calculations, the SWS has been characterized using liquids with a controlled refractive index. For this a cuvette has been clamped on top of the sensing region and varying benzyl-alcohol/alcohol mixtures were fed into the cuvette. The index of this mixture was measured with an Abbe refractometer (accuracy ± 5.10^{-4}, white light). A single mode input fiber is attached to the chip using a V-groove. A multimode fiber is used for the output. The output power was measured as a function of Δn. A typical experimental result is shown in figure 3. As can be seen η (Δn) is approximately a square function, which means that the sensitivity is approximately a linear function of Δn.

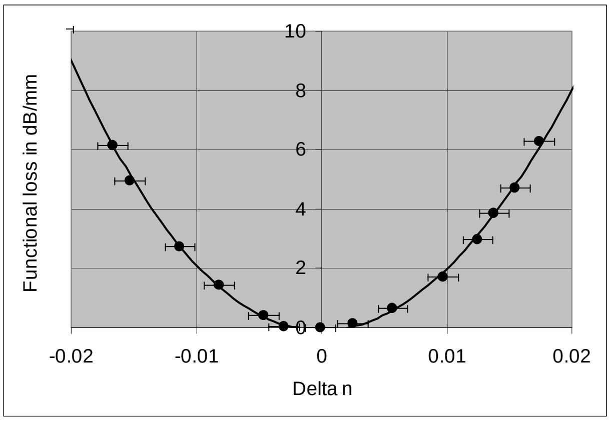

Figure 3. SWS characteristic for L = 9 μm, measurements (points) and simulations (line)

Because of the temperature dependent index and the unknown dispersion, the absolute refractive index of the mixture could not be determined exactly, therefore the whole characteristic has been shifted along the Δn- axis to put the minimum in functional loss at Δn = 0,while the transmitted power at minimum loss itself has been taken as the reference power. The uncertainty in absolute value of Δn is the main contribution to the error bars in figure 3 and 4. In figure 4 both the experimentally obtained and theoretically calculated η(L)- dependences are presented. for Δn = ± 0.01.

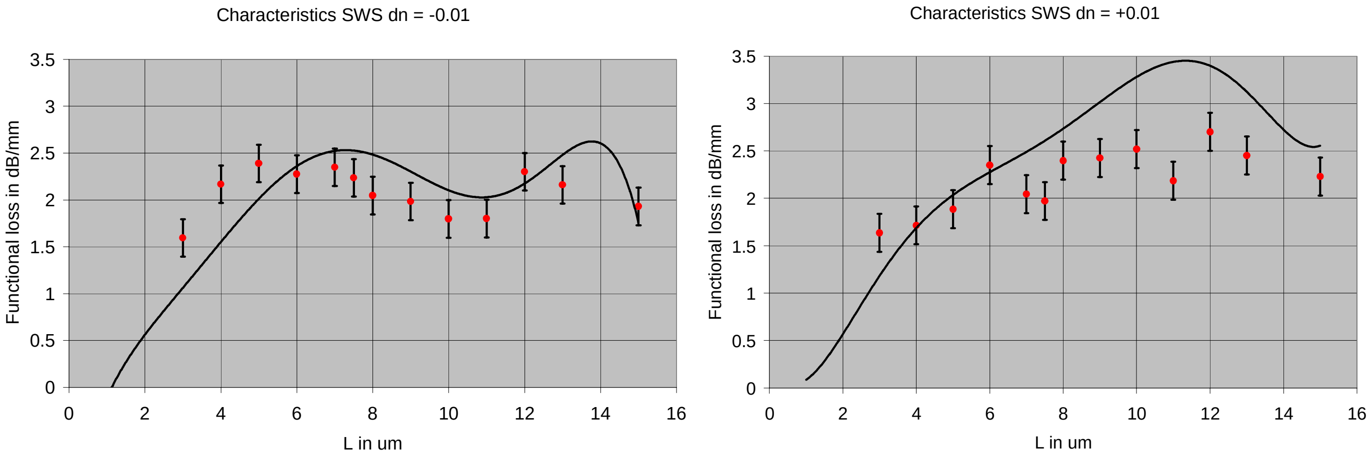

Figure 4. SWS characteristics for different L, measurements (points) and simulations (line)

As can be seen, the experimental points agree reasonably well with the theory. We suppose that their difference can be attributed to the fact that all the calculations were done in 2D and not in 3D. Further it can be seen that it is important that L > 5 µm; the highest sensitivities are obtained for these L-values. In this region the dependency of the sensitivity on L is small.

From these measurements the resolution can be derived. From figure 3, it can be concluded that the sensitivity (proportional to the slope of the characteristic) increases linearly with Δn. Hence the further away from $\Delta n = 0$, the larger the sensitivity. We define Δn_w as the refractive index difference at the concentration around which small concentration changes have to be measured. The sensitivity now increases linearly with Δn_w, but the non-functional loss increases with $(\Delta n_w)^2$. Therefore it is more efficient to make the SWS as long as possible and to choose Δn_w close to zero. The propagation losses eventually limit the size of the sensor. Channel losses of the individual segments have been measured to be less than 1 dB/cm. Besides the optical part, also the processing electronics influence the resolution. For the derivation of the resolution a commercially available optical detector with an accuracy of 0.01 dB and a noise level of –90 dBm was taken. Further constant temperature and constant light source power was assumed. After optimizing the segment length and the Δn_w, a theoretical resolution of $\Delta n = 5.10^{-7}$ is theoretically feasible. Adding a reference channel can reduce the influence of disturbances like fluctuations in power and polarization of the light source. We also expect that the resolution can be improved by smart processing schemes. There are also several other possibilities, not mentioned in this paper, for improving the optical part of the SWS.

Summary /Conclusions

The principle of a novel type of a refractive integrated optical chemical sensor, the segmented waveguide sensor, has been explained. This sensor combines a simple technology with a resolution in the refractive index of the chemo-optical transduction layer better than 5.10^{-7}. Experimental performance, measured on a sensor fabricated in SiON technology agrees reasonably well with the theoretical performance as has been calculated by applying several 2D simulation programs. Optimization of the sensing system is expected to enable improved performance.

[1] P.V. Lambeck, *ECIO 2001*, pp. 153-163, 2001

[2] K. Wörhoff, P.V. Lambeck, A. Driessen, *J.Lightwave Techn.*, Vol. 17, No. 8, 1401-1407, 1999.

[3] OlympIOs; *C2V software*, version 5.1.12

[4] S. Gaál, doctoral thesis, Lightwave Devices Group, University of Twente, dec. 2002.

[5] H.J.W.M. Hoekstra, S. Gaál, P.V. Lambeck, *ECIO 2003*, to be published.

[6] R.G. Heideman, P.V. Lambeck, *Sensors and Actuators B*, vol. 61, 100-127, 1999.