Extended Paper

Chemo-optical micro-sensing systems

Paul V. Lambeck

MESA-institute, University of Twente,
P.O.Box 217, 7500 AE Enschede, the Netherlands.

ABSTRACT

Chemo-optical micro-sensing systems, whether based on fiber optics or integrated optics show promising prospects. The physical principles underlying chemo-optical waveguide sensors are discussed with the accent on linear evanescent field sensors. The role of the chemo-optical transduction layer is emphasized. Restriction of the freedom of design by technological uncertainties is briefly dealt with. The structure of a complete micro-sensing system is discussed, and illustrated by presenting various designs of chemo-optical sensors based on Surface Plasmon Resonance.

1. INTRODUCTION

Chemo-optical waveguide sensors are penetrating the sensor market slowly. Although quite a number of waveguide concepts show very promising prospects, material sciences and technology in this area have not reached the level required for implementing these concepts into cheap sensors with the aimed performance. Considering the limited investments the relatively small sensor market can afford, this situation might be alarming. Fortunately, the waveguide sensor development can proceed in the slipstream of powerful markets, such as: (optical) telecommunication and electronic integrated circuits, taking advantage of the progress in this fields. Besides this there is an impressive gap in the market arising especially from the need of environmental measurements.

In general, attractive aspects of optical sensing are: no e.m. interference, no danger of explosions, and the large sensitivity that can be obtained by using optical methods. Extra impulses arise from the present availability of cheap light sources (e.g. laser diodes) and detectors (photo-diodes). By utilization of the waveguiding phenomenon new strong points are added. For example a simple control of the light path (without using bulky components such as mirrors and beamsplitters), and the potential of easily processing the light propagating through the optical circuitry.

Here we will focus on integrated optical (I.O.) sensors, although sometimes to fiber-optic ones. I.O. sensors are small planar monolithic multilayer systems, acting as a complex of optical functions (optical chip). This multilayer structure can be realized by applying physical and chemical deposition and/or diffusion technologies for building the layer structure; photolithography and etching methods are used for lateral structuring (wave guide channels). The I.O. sensors have some strong points, which are absent or less pronounced in fiber-optic ones:

- large flexibility in the choice of constructing materials, affording sensor types, not realizable with today's fiber optics,
- all required basic functions can be realized simultaneously,
- batch-wise mass production,
- small and rugged,
- prospect of monolithic smart multi sensor systems.

Compared with integrated optic sensors, fiber sensors have their specific strong

points too:

- the commonly available optical fibers are cheap,
- they are easily inserted in remote sensing systems or fibre optic sensor networks without the need of fiber-chip coupling.

There is a prospect of hybrid chemo-optical evanescent field sensors, consisting of a polished fiber-block or a D-shaped fiber, on top of which in the evanescent field region of the fiber mode a multilayer structure has been built up. Another type of hybrid sensor may contain a mixture of fiber-optic and integrated optic basic functions, such as already has been realized in fiber-gyros, for example².

The multidisciplinary nature of sensor research reflects itself in the structure of this paper:

In section 2 physical chemo-optical sensing principles will be classified, and some examples will be given. The chemo-optical transduction layer, interrelating the chemical and optical domain, will be treated shortly in section 3, while various sensing parts will be evaluated in section 4. The next section 5 deals with materials and technologies and presents some rules of thumb on how to handle the inherent technological uncertainties. In section 6 attention is paid to complete chemo-optical sensor systems and some lay-outs, all based on the Surface Plasmon Resonance principle will be presented in section 7. The last section 8 summarizes the main conclusions.

2. CHEMO-OPTICAL SENSING PRINCIPLES

In fiber-optic sensors, fibers are sometimes introduced solely for the transport of light to and from the sensing region, where it is modulated due to the presence of the chemical species (an extrinsic sensor). In contrast all I.O. sensors are intrinsic; along the entire sensor system the (relevant part of the) light propagates as guided modes.

As in most sensor fields we can distinguish between sensors of the generator or modulator type. In the first type of sensor particles of the measurand initiate a chemical reaction, acting either as a reactant or as a catalyst, leaving behind one of the reaction products in an excited state. These excited molecules return to the ground state under emission of light, known as chemiluminescence¹. Photons emitted in the evanescent field region of a waveguide are partly captured by the waveguide, resulting in the generation of guided modes. Although the sensitivity, which can be obtained from these generator-type sensors is impressive, the majority of the chemo-optical sensors are of the modulator-type in which one of the characteristic parameters of an incoming mode is changed by the measurand; the magnitude of that change usually represents the concentration. We will focus on the latter type.

Some I.O. chemo-optical sensors have been reported based on concentration-induced changes of optical properties of the core of the waveguide³. However the large majority utilizes the concentration dependency of cladding properties probed by the evanescent field (evanescent field sensors). According to the character of the physical phenomenon that has been used for transducing chemical concentrations into changes of optical properties the evanescent field sensors can be divided into two classes: linear and non-linear.

In the latter class non-linear effects such as luminescence or Raman effect are utilized. The non-linear sensors show different frequencies of the input light and the relevant output light. Photons from the incoming mode (frequency ν_1) excite active centers, located in the evanescent field region, the number of these centers being dependent on the concentration of the chemical species to be measured. After activation these centers in turn can emit radiation of another frequency (ν_2). Due to the evanescent fields a remarkable large part of the emitted light is trapped by

the waveguide, resulting in generation of guided modes of frequency ν_2 . The concentration can be deduced from the ratio of the input and output intensities $I(\nu_2)/I(\nu_1)$.

Here we shall focus on linear sensors, in which the sensing is based on the concentration (C)-dependency of the complex dielectric constant $\tilde{\epsilon}$ ($= \epsilon' - j\epsilon''$) of (parts of) the materials in the evanescent field region.

Changes of this dielectric constant, will be manifest as changes of the (complex) propagation constant $\tilde{\beta}$ ($= \beta' + j\beta''$) of the modes propagating through the waveguide. By applying proper detection principles this $\tilde{\beta}$ change can be transformed into an intensity change, which can be easily measured.

Hence, we are utilizing the transduction chain:

This linear sensor class in turn can be divided into two subclasses, according to the utilization of the change in the real or imaginary part of the dielectric constant. Thus we can distinguish refractive sensors ($\Delta\epsilon' \rightarrow \Delta\beta'$) and absorptive sensors ($\Delta\epsilon'' \rightarrow \Delta\beta''$).

Changes in the real part of the propagation constant result in changes of the phase of the mode. This phase change can be transformed into an intensity change by use of the optical interference phenomenon (for example in a Mach-Zehnder interferometer^{4,5}). In some read-out methods the interference phenomenon manifest itself as a resonance: Fabry-Perot resonator⁵, ring resonator and all methods based on mode coupling, (e.g., surface plasmon resonance⁶, and grating assisted coupling into radiation modes⁷).

Changes of the imaginary part, ϵ'' , will result directly in changes of the attenuation⁸ of the mode, which can be measured as the ratio between in- and out-put intensities^{9a,b}. Also more sophisticated methods have been developed, like luminescence quenching^{9a,b} and application of the absorption dependency of the Finesse of F.P. resonators¹⁰. Most of these read-out methods are visualized in fig. 1.

Because all these sensors are based on modulation as well as the output signal a reference signal is often required. If the output is obtained as an intensity, the value of the input intensity is needed, which can be obtained by guiding part of the input light into a reference channel. In principles based on mode coupling, modifications exist that make use of a shift of an angle which is characteristic for an intensity extremum; they require knowledge of a reference angle related to a known concentration.

3. THE CHEMO-OPTICAL TRANSDUCTION LAYER

Up to now we have not discussed the way chemical concentrations may influence the optical properties of the cladding region.

For simple problems, such as measuring high concentrations of strongly absorptive entities by the absorption method or measuring the composition of water-acetone mixtures by SPR-method¹¹, it is sufficient to fill the evanescent field region with the solution itself. The sensitivity can be increased strongly by the introduction of a chemo-optical transduction layer. Herein entities of a compound X, of which the concentration has to be measured, are concentrated due to a (preferentially reversible and selective) association with molecules A, which have been immobilized in that layer.

Fig. 1 Some optical sensing principles: Interferometry⁴, Surface Plasmon Resonance (SPR)^{6,9,11,12}, Absorption⁸, Luminescence Quenching^{9a,9b}, and (grating-assisted) wavelength selective coupling.

As an example we mention immunosensors in which immobilized antibody molecules act as A molecules and are able to associate selectively with specific antigens X. Associated antigens displace solvent molecules, causing changes of local refractive indices in the evanescent field region. The resulting $\Delta\beta'$ can be measured by SPR⁶ or interferometry⁴. As well as concentration the transduction layer can accomplish amplification of optical effects if the A molecules have been properly tailored. In an absorptive sensor for example, this can be achieved by using molecules A, deliberately fitted with strongly absorbant groups, and so constructed that after association the absorption band is shifted to a wavelength region that contains the wavelength of the guided light. Thus the chemo-optical transduction layer acts as a selective low-noise pre-amplifier for the optical detection circuit. Sometimes well-known materials can be used, for example the pH-indicator Bromo Cresol Purple, for ammonia-detection¹². Nevertheless molecules of a new type, with a

performance well matched to the requirements of the measuring problem often have to be designed (molecular engineering) and synthesized.

In fig. 2 we present an example, a chromoionophore, that shows a strong preference to associate with calcium ions; the association resulting in a shift of the relatively narrow absorption band of about 90 nm¹³.

Relevant properties of the A-molecules are:

- the constants $K_{ass}(X_i)$. They define the affinity to the chemical species X_i and determine the centre of the dynamic range,
- the values of the reaction rate constants k_1 and k_2 co-define the response time,
- the difference in optical properties between the A and AX molecules is relevant for sensitivity and resolution.

Also the structure of the transduction layer i.e. the density of incorporated A-molecules, the layer thickness and the diffusivity of X molecules, co-define sensitivity, resolution and response time.

In the following table relevant chemo-optical sensor properties are classified according to their origin, whether transduction layer or optical detection system.

Fig. 2. Chromoionophore based on a phenolic crown ether and a merocyanine dye¹³.

	Transduction layer	Optical detection system
Selectivity	**	
Dynamic range		
- centre	**	
- magnitude	*	*
Sensitivity	*	*
Resolution	*	*
Response time	**	
Calibration	(*)	*
Reproducibility	*	*
Stability	*	*
Costs	*	**

4. EVALUATION OF SENSING PARTS

Now we shall discuss some strong and weak points of the various sensing principles. We emphasize that the relevance of each point will be determined by the particular application we have in mind. Selectivity, for example, is irrelevant if it is assured that the chemical system will contain one compound only. Sensitivity and resolution are determined by the signal/noise ratio. The noise results from fluctuations of some other physical parameters, Uncertainties in geometry, in losses

and in refractive indices of the waveguide channels due to technological limitations will lead to a spread of scale-factor and offset-values. Of course the influence of the latter factor can be remarkably diminished by tuning and calibrating the sensors individually.

The main physical sources of noise are intensity variations of the light source, detector noise, temperature fluctuations and environmental influences from outside the transduction layer, including contamination. If detector noise is dominant in absorptive or interferometric sensors, the sensitivity can be increased by enlarging the interaction length. This enlargement, of course has its limits too, e.g. the (scattering in) losses of the bare waveguide channel.

The influence of *temperature fluctuations* can be decreased in the Mach-Zehnder interferometer, by bringing both branches close together, avoiding mode coupling, as is quite possible in an integrated optic layout. The association constant K_{ass} however, may be very temperature sensitive, enforcing for example the inclusion of a temperature sensor. A short *response time* generally requires a thin transduction layer. The thinner the layer, the smaller the part of the optical energy propagating through this layer and thus the smaller the sensitivity. As to this aspect surface plasmon modes are superior to waveguide modes, because in the former the energy is concentrated in thin layers near the metal-dielectric interface.

Using thin transduction layers favours the *interference of environmental* changes of the complex dielectric constant. In sensors like the absorptive and interferometric ones this interference can be compensated for by proper referencing. The luminescence quenching sensor^{9,14}, figure 1, is very insensitive to these changes, because the short range of the radiationless energy transfer usually limits the quenching action to the first two or three molecule layers of the transduction layer. Because each absorption centre, at the interface between luminescent and transduction layers, is generally capable of quenching numerous excitons an extra signal amplification is obtained. *Contamination* can be prevented by screening the transduction layer from the environment by a (vibrating) membrane permeable by the chemical species to be measured; of course this method is disastrous for the response time. Contamination influences can be reduced by probing the transduction layer with several guided modes¹⁵.

Here we shall not discuss the benefits of introducing modulation methods into these sensor systems.

Because most physical phenomena, that are applied in these sensing principles, can be described macroscopically quite well, some aspects of the performance of a given sensing structure can be calculated numerically, using simulation programs. If necessary the sensing part can be optimized as to given criteria, although incorporation of technological tolerance is cumbersome. We will discuss this subject in more detail in section 5.

At this time it would be premature to present a final judgement of the potential of the various chemo-optical sensing principles, because strongly determining factors such as technological control and design as well as the synthesis of transduction layers are still in a virulent state of development.

5. MATERIALS AND TECHNOLOGIES, TOLERANCES

5.1 Introduction

In this section we shall restrict ourselves to integrated optic sensors, where the sensing part is one of the constituents of an optical circuit, as will be treated in more detail in section 6. In designing IO-sensors, mutually strongly related choices have to be made as to the materials, technologies and optical basic functions, that will be applied.

For designing sensors in an efficient way, it is advisable to consider at first known materials, technologies and even known basic functions, and if necessary to think about designing new ones at a later stage only. It can be seen that, in general, development of new optical materials or new technologies requires much more efforts, consuming much more time and money, then designing theoretically new optical functions. However, it is challenging to think of new materials, new technologies and to speculate about their prospects in IO sensor systems. This is often just the starting point of very interesting new sensor developments.

Materials support the physical phenomena that have to be utilized in specific applications. In the optical field we distinguish between active and passive materials. This is more an engineering classification than a physical one. Active materials are materials in which physical cross-effects, relating the optical domain to another physical domain, are utilized to introduce dynamics into optical functions. These active functions receive control signals, effectuating changes in optical properties due to the cross-effects. These changes can be used to accomplish actions like switching or tuning. The most important cross-effect is the electro-optic one.

Although principally all materials show thermo-optic, elasto-optic and opto-optic cross-effects, they are called passive if the effects are too small to be useful, or if the optical function in which they are incorporated does not respond to them. The values of material parameters depend on the technological parameters of the fabrication process. On the one hand this dependency offers an attractive possibility for tailoring optical materials, but on the other it is responsible for harmful non-uniformity and non-reproducibility of optical properties such as refractive index and losses. Also geometric characteristics (layer-thickness and lateral dimensions) are subject to technological fluctuations.

These technological tolerances result in spreads of the scale-factor and the offset-values of the sensor. They attack the correct action of functions, even making critical functions such as wavelength filters, based on grating-assisted mode-coupling, completely ineffective. Basically it is the resulting spread in propagation constants, field profiles and interaction length, that degrades the performance.

Thus an essential characteristic for the quality of materials is found in the spread in relevant properties as well in one particular circuit as from batch to batch. It seems to be appropriate to characterize this quality by a tolerance vector, located in an n -dimensional space, each component representing the relative uncertainty of a particular relevant property.

5.2 Materials

Excluding III-V compounds and LiNbO_3 as being too expensive for sensors the materials mainly used for IO-sensors are indiffused glasses, polymers and (doped) SiO_xN_y , the first two materials being relatively cheap.

At present there is a good understanding and control of the processes going on during the production of indiffused glass waveguides and they can be achieved with a uncertainty of the propagation constant in the order of magnitude of $10^{-2}\%$ ¹⁶. Losses smaller than some tenths of a dB/cm are obtained. The thermo-optic coefficient of the commonly used BK-7 glass is low ($dn/dt \sim 10^{-6}/\text{K}$) limiting severely the tuning possibilities.

Polymer layers, such as PMMA, PVD, PUR, etc. can be produced easily by spinning or dipping. A reproducibility in a thickness of about 1% is easily obtained¹⁷. Losses are smaller than some tenths of a dB/cm. Thermo-optic coefficients are relatively high. Nevertheless these layers are seldom applied, mainly because of degradation phenomena. It should be mentioned however, that up to now efforts to optimize

passive polymers for use as an waveguiding material have been small. At present the development of electro-optic polymers, showing electro-optic coefficients equal to those of LiNbO_3 , will initiate new research on that aging behaviour, and that will be important for other polymers too.

An attractive combination of indiffused glasses and polymers can be obtained¹⁸: indiffused glass channels are used as "ridges" for the definition of waveguide channels in the polymeric core layer, spun upon the glass-substrate. Thus the necessity is avoided of learning all details of the lateral structuring of each individual polymer as well as the planarization problem. If the polymer could be electro-optic cheap circuits containing passive as well as active functions could be obtained.

Another approach is followed by groups at LETI¹⁹, AT&T Bell²⁰ and Hamburg-Harburg University²¹, using Si-wafers as a substrate and (P-doped) SiO_2 or SiO_xN_y materials known from IC-technology as waveguiding materials. Multilayer structures can be realized in one run using CVD-technology.

The advantages of these structures are summed up extensively in²⁰ and²². In general this approach results in low-loss waveguides. As far as is known the uncertainty in the thickness of the layers amounts to some percent, and a wafer-to-wafer refractive index accuracy of better than 0.2% can be obtained. Papers from AT&T Bell²³ even suggest an accuracy of about $10^{-2}\%$. For the SiO_2 - TiO_2 waveguides, made by flame hydrolysis by NTT²⁴ no explicit data concerning reproducibility are presented in literature.

5.3 Tolerances

How can these tolerances in IO-sensing circuits be dealt with? There are various approaches.

- Concentration on technological improvements,
- Fabrication of a large number of circuits, hoping that one of them will show the required parameter value, presenting it as a prototype,²⁵
- Trim and tune the sensors individually. A good example²⁵ is the laser trimming of an 3 dB coupler, realized in SION technology to an accuracy of about 3%. Physical tuning of refractive indices, using cross-effects results in small changes only: electro-optically and thermo-optically at most in the order of magnitude of 0.1% and 1% respectively. In some cases these small changes are very effective already, e.g. in the case of an Y-junction splitter with tunable power ratio, or for tuning a Mach-Zehnder interferometer.
- One can learn from simulating the effects of the individual tolerance components on the performance of a particular function, relating components of the tolerance vector, free function parameters and function performance.

The function can be optimized as a compromise between two criteria: optimal performance and minimal influence of tolerances on the performance. In optical circuits, consisting of more functions, the number of degrees of freedom is reduced; it is practical that all functions are built from waveguiding layers having the same composition and thickness. Making a library, containing all functions and all common optical waveguide materials, seems to be too ambitious. In a first stage however we can try to find some trends and maybe some rules of the thumb.

Here we present two examples:

- the influence of dimensional uncertainties on the absolute value of the propagation constant can be reduced considerably by producing low contrast waveguides, i.e. waveguides with a small difference between the refractive indices of core and core-surrounding materials (see fig. 3).

Fig. 3. a) Low contrast waveguide structure
b) $N_{\text{eff}} \equiv \beta/k_0$ of the TE_0 mode as a function of the core thickness t .

- equality of propagation constants of two channel guides is relevant for many functions, not their absolute value, e.g. couplers, 1:1 Y-junction power splitters, reference branches, etc. Because in these functions both channels are located close together, differences in refractive index and layer thickness will be small, and especially for narrow channels the uncertainty in channel width may be dominant. As an example we present some BPM-simulations of a monomode "symmetrical" 1:1 Y-junction splitter, with a small exit angle 0.2° to minimize forward scattering. The channel width is $4 \mu\text{m}$. In order to make the effects more dramatic we have incorporated the Y-junction in a Mach-Zehnder interferometer.

Fig. 4. BPM-simulations of the light propagation through a Mach-Zehnder interferometer

- a) structure
b) completely symmetric
 $d_1 = d_2 = d = 4 \mu\text{m}$
c) asymmetric Y-junction
 $d_1 = 3,8 \mu\text{m}$
 $d_2 = 4,2 \mu\text{m}$

Fig. 4b concerns an ideally symmetric interferometer. Next the upper channel is widened $0.2 \mu\text{m}$ along a distance of $2800 \mu\text{m}$. Fig. 4c presents the simulated

performance. Although the change is propagation-constant caused by the widening is relatively small (4 %), it causes a power splitting ratio of about 1:2 instead of 1:1, and besides this an extra phase difference between both branches. Of course the asymmetry of power splitting can be strongly reduced by choosing a larger exit angle at the expense of larger losses.

6. CHEMO-OPTICAL SENSOR SYSTEMS

In order to achieve a complete sensing system, the bare sensing part has to be extended with other functions, such as

- light source,
- conditioning functions, which extract the components required by the particular sensing principle from the light offered by the light source,
- processing functions required to offer the concentration information as an intensity to detectors,
- detectors and electronic circuitry to process the detector signals.

Fig. 5. Basic sensing system structure.

A symbolic set-up of a complete sensing system is presented in fig. 5. Such a system can be built from bulky components, fiber-optic components interconnected by fibers, integrated optics or hybrid types. In principle the complete system can be integrated into one electro-optical sensor chip (smart sensor). Using a Si-wafer as the substrate for the optical circuitry, detectors and all electronic circuits, required for tuning, activation and processing can be implemented in the wafer itself. Miniaturization can be completed by mounting a laser-diode on the chip. If required, for example for saving the e.m. no-interference, functions can be distributed over several subsystems, interconnected by fibers.

Cost reduction can be obtained by developing families of sensors for related applications, the members differing in one aspect only, e.g. the applied transduction layer. This is a complicated task, because predictions about the needs of "the" market has to be combined to expectations on price and performance of sensor systems, the latter not limited to optical sensors, but comprising sensors such as ISFET's and mechanical ones too. Specific submarkets have particular wishes. For immunological sensing in laboratory an expensive detection system, constructed with cheap disposable sensing parts will be very adequate. For routine environmental sensing the small self-supporting sensing systems from the integrated optics are preferable.

No general rules for starting sensor development can be given; all that can be done is making a first choice for a specific application area on strong and weak points

of all the variable entities, involved in sensing systems, preferably combined with some original ideas.

Other approaches are possible, e.g. starting from a particular principle, material or technology and imagining its application in sensor systems. An example will be given in the next section.

7. CHEMO-OPTICAL SENSORS BASED ON SURFACE PLASMON RESONANCE

Some metals are able to support Surface Plasmons (SP's) i.e. guided modes propagating along the metal-dielectric interface. The field of such a TM-mode is evanescent at both sides of the interface, and is concentrated in a thin interface region ($\sim 1 \mu\text{m}$). Thus the propagation constant of the surface plasmon, β_{SP} will be very sensitive to ϵ -changes of the transduction layer deposited on the metal surface.

Fig. 6. a) Kretschmann configuration

b) Reflection curve: Reflection R as a function of the angle of incidence θ .

β_{SP} can be read out by the attenuated reflection method, based on mode coupling. In the Kretschmann-configuration²⁶ (fig. 6a) a light beam with an angle of incidence θ will be totally reflected, unless the coupling condition $\beta_{\text{SP}} = \frac{2\pi}{\lambda} \sin \theta$ is fulfilled. In that case the excitation of the surface plasmon caused by mode coupling with radiation modes will cause a frustrated reflection. Because of the lossy character of the SP, this resonance is observed as a dip in the reflection curve $R(\theta)$, with a non-neglectable bandwidth (fig. 6b). This resonance dip will shift along the θ -axis, as a consequence of ϵ -changes of the transduction layer. $R(\theta)$ can be measured by rotating the sample. By using a slightly converging incident beam, the complete reflection curve²⁷ can be obtained instantaneously by imaging the reflected light on a diode array. Starting from a given error in measuring intensities the plasmon supporting multilayer structure can be optimized to maximum resolution²⁸. It can be produced as a disposable. Resolution and sensitivity can be increased by using Long Range Surface Plasmons²⁹.

This read-out method based on mode coupling can be easily implemented in waveguiding systems. Here β_{SP} can be probed by offering the SP-supporting structure guided modes from a waveguide¹⁴ (fig. 7a). By launching polychromatic light into a monomode waveguide, a range of β -values is offered, each wavelength corresponding to a particular β -value. Now the concentration-information is presented by the wavelength dependency of the output light, which can be analysed by use of a monochromator. This expensive apparatus can be avoided by another design, using an array of channel waveguides with different cross-sections, each provided by the transduction layer¹⁴ (fig. 7b). The reflection curve is offered as the intensity distribution over the output of the different channels. In principle the reflection curve can also be measured as a function of time, using the monolithic IO-sensor suggested in fig. 8.

Fig. 7. a) Schematic cross-section of a SPR-waveguide sensor (wavelength selective design). 2: SiON-waveguide; 6: SP-supporting metal layer; 1,3,4,6: buffer layers.
b) Schematic drawing of a SPR-waveguide-array sensor.

The system consists of a network of monomode guides, built upon a Si-wafer, in which detectors and electronic circuits are implemented. A cheap broad-band laser-diode (BBL) is mounted on the chip as a light source. TE-modes being superfluous because TM-modes are effective only, are drawn off by using an asymmetric Y-junction (MSY). A dynamic wavelength filter (DWF) offers an output of which the wavelength varies with time in a well-defined way. Next the light enters a symmetrical Y-junction (PSY), where it is divided over two channels, one supporting the SP-structure, the other for referencing. The concentration can be obtained by electronic processing the detector outputs.

Fig. 8. Potential IO-sensing system, based on Surface Plasmon Resonance.

8. CONCLUSIONS

Chemo-optical waveguide sensors show very promising prospects. Some of them arise from general properties of optical measurement methods: no e.m. interference, explosion-free and potentially large sensitivity. The use of waveguides contributes other strong points, such as simple control of the light path and the potential of easy processing of the light.

Fiber-optics as well as integrated optic chemical sensors show their particular strong and weak points and preference for one of them strongly depends on the special application the designer has in mind.

A large number of physical principles are available for sensing chemical concentrations using optical waveguides; examples are: extrinsic or intrinsic, generator or modulator types and as a subdivision, linear and non-linear ones. By

introducing the chemo-optical transduction layer selectivity and a strong sensitivity enhancement can be obtained. Each physical principle has its particular set of strong and weak points, some of a purely fundamental nature, while others are strongly dependent on the present state of technology, by which uncertainties into optical properties and geometrical dimensions are introduced. Frequently these uncertainties will be decisive when choosing the best principle, the best material and the best technology for a particular application.

Although each application has its own particular requirements, it is advisable to design families of sensors, in which the members differ in only a limited number of parameters. The sensing part can be inserted in a complete sensor system. Using integrated optics in which the multi layer structure is built upon a Si-wafer, all the required functions, optical as well as electrical, can be implemented in one monolithical chip, even potentially offering smart multi sensor chips.

In the present state, the chemo-optical sensor research has hardly left the stage of designing and realizing prototypes. A lot of effort has to be put into the design of adequate chemo-optical transduction layers, and in improving the technologies applied for realizing the optical system. As to the latter the sensor development will take every advantage of the progress of expertise in powerful markets, like telecommunication and electronic integrated circuits.

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