Low-loss PbO$_2$ diffusion waveguide used as a sensitive gas sensor

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A fast-response integrated opto-chemical sensor system can detect ultra-low concentrations of ammonia with high reproducibility.

The detection of dangerous and harmful gases represents an important issue in ecology, chemistry, environmental monitoring, and defense. The control of atmospheric ammonia levels is especially important because it is a flammable and explosive gas. Apart from its natural origin, it has many sources. Besides the chemical industry and livestock farming, the growing micro-electronic industry also generates ammonia during photolithographic processes.

Among those available, integrated opto-chemical sensors are most promising. Their working principle is based on the variation in the transmission of certain property-dependent laser wavelengths by the gas or liquid being monitored. The main challenge is to elaborate an easy-to-use, compact, accurate, and reliable sensor with a fast signal response for measuring the atmospheric concentrations of various substances, including ultra low levels.

We previously described an opto-chemical sensor scheme featuring a resonance amplifier and lock-in detector with mechanical recording of the output signal. However, the measurement setup had the following drawbacks: a time response exceeding one second, the production of analog signals, and a high sensitivity to mechanical noise. Laser power losses were also very high in the optical waveguides, to the point of affecting the metrological characteristics of the sensor.

As a result, we directed our efforts towards elaborating the new opto-electronic system illustrated in Figure 1. The radiation source is the 632.8nm line of a He-Ne laser, which coincides with an absorption band of ammonia (NH$_3$). The incident beam is split into reference and sensor beams by a half-transparent mirror. The sensor beam is directed into an integrated optical sensor cell at an angle that corresponds to the resonant excitation of the TE$_0$-mode. The sensor is a diffusion planar waveguide fabricated by doping a glass substrate with PbO$_2$. The cell length, i.e. the distance between the input and output prisms, is 4cm. The coupling prisms are made of TF-5 glass with a refractive index of 1.7497 at $\lambda = 632.8$nm. Waveguide attenuation is 0.1cm$^{-1}$ for the fundamental TE-mode with an effective refractive index $n_{eff}$ of 1.521.

The radiation emerging from the waveguide output prism is measured by a photodetector, whose signal is fed to a comparison microelectronic device. The signal of the reference beam, measured with a second photodetector, is also fed to the same device. After analog-to-digital conversion, the signal is recorded and processed with a computer. The comparison device consists

Continued on next page
of precision amplifiers with small displacement voltages and high voltage amplification factors. They can perform frequency correction and have a well-balanced combination of input voltages and noise current that provides high stability to the comparison device against mechanical and other noises. Figure 2 shows a top view of a tested integrated optical waveguide cell.

Ammonia concentration is easily calculated using the Bouguer-Lambert-Beer law,

$$P = P_0 \exp(-l \sigma N)$$

(1)

where $P_0$ is the radiation power at the output of the cell in the absence of ammonia, $P$ is the output power in the presence of ammonia, and $l$ is the thickness of the layer of the medium, which corresponds to the length of the absorbing cell. The absorption cross-section of the ammonia sample is $\sigma$ and $N$ is the measured concentration. At the He-Ne laser wavelength ($\approx 0.63 \mu m$), $\sigma_{NH_3} \approx 3.8 \times 10^{-16}$ cm$^2$.\textsuperscript{6} Rearranging Equation 1 then yields the ammonia concentration as

$$N_{NH_3} = \frac{\ln(P_0/P)}{\sigma_{NH_3} l}.$$ 

(2)

Using the data obtained from the waveguide cell shown in Figure 2, we were able to use Expression 2 to determine an ammonia concentration of approximately 4 ppm.

Similarly, the ammonia concentration measured at the limiting sensitivity of the waveguide sensor can be obtained using:

$$N_{NH_3}^{\text{min}} = \frac{\ln(P_0/P_{\text{min}})}{\sigma_{NH_3} l}.$$ 

(3)

Here, $P_{\text{min}}$ is the noise level measured at the cell output in the absence of ammonia. Using this expression, we calculated $N_{NH_3}^{\text{min}} \approx 0.1$ ppm for a signal-to-noise ratio of about 20.

Figure 2. Top view photograph of a tested integrated optical waveguide cell showing the input (1) and output (2) prisms, the integrated optical waveguide (3), and the TE$^0$-mode track (4). When ammonia is delivered to the sensor cell, the output laser power decreases.

Figure 3. Reproducibility test of our integrated opto-chemical waveguide sensor.

Figure 3 shows a representative test showing that reproducible ammonia concentrations could be measured with our integrated optical waveguide sensor system using the PC-Lab 2000 virtual laboratory package as a transient recorder. The mean voltage deviation for ammonia detection from the average value did not exceed 5%.

In summary, we have described our improved integrated optical-waveguide chemical-sensor system applied to the detection of ammonia. These sensors are also attractive for monitoring both gaseous pollutants and substances dissolved in liquids for a variety of biomedical, physicochemical, and environmental measurements. Of interest is also their potential integration in optoelectronic air quality control systems.

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Continued on next page
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